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**INVESTIGATION OF COORDINATED FREE TURBINE
ENGINE CONTROL SYSTEMS FOR MULTIENGINE HELICOPTERS**

By

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December 1967

**U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA**

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This Command has reviewed this report and concurs
in the conclusions contained herein. The findings
of this report will be used during future studies
related to multiengine helicopter propulsion
control.

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**INVESTIGATION OF COORDINATED FREE TURBINE
ENGINE CONTROL SYSTEMS FOR MULTIENGINE HELICOPTERS**

Final Report

EDR 5298

by

R. M. Swick and C. A. Skarvan

Prepared by

**Allison Division • General Motors
Indianapolis, Indiana**

for

**U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA**

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SUMMARY

The objectives of this program were to analyze and evaluate various control concepts for the multiengine helicopter to arrive at a definition of an optimum system design. Hopefully, this system would relieve the pilot of the responsibility of continuously monitoring the operation and performance of the multiple engines during critical flight maneuvering.

This program consisted of three principal phases: evaluation of power turbine governing modes, evaluation of the gas producer control requirements, and evaluation of multiengine governing-load sharing concepts. The final result was the definition of a control system design coordinated with respect to the functional characteristics and required scheduling.

The evaluation of power turbine governing was directed toward defining the optimum power turbine governing mode for a helicopter gas turbine engine. This evaluation showed that a proportional power turbine governor with a lagged gain reset (feedback) is the desirable mode. The major criteria in this evaluation were governing stability and power transient response. The stability analysis was based on a linearized representation of the engine-controls-rotor system and included both Bode diagram analysis and analog computation. The transient response investigation involved a nonlinearized digital computer simulation of the different modes and the engine and rotor system, with collective load transients imposed.

The evaluation of gas producer control requirements was directed toward determining those special features required for the multiengine helicopter powerplant. The operating requirements of the engine and helicopter were defined and evaluated with regard to engine control. Some of the specific control features determined to be necessary are automatic start sequencing, closed-loop steady-state turbine temperature limiting, emergency power operation capability with both manual and automatic selection capability, and power turbine governing action accomplished by means of the gas producer control fuel metering valve.

The multiengine governing-load sharing concept evaluation was conducted to determine the optimum concept based on the governor mode and gas producer control design determined to be most promising. The selected concept utilizes individual governors for each engine, with closed-loop load sharing control and an automatic engine malfunction detector. A digital computer simulation of the more promising control schemes and a multiengine-helicopter power system was developed and utilized in steady-state and transient analyses. Block diagrams and component schematics were generated to aid in the evaluation with regard to mechanical design complexity.

FOREWORD

This is the final report on the Allison project entitled "Investigation of Coordinated Free Turbine Engine Control Systems for Multiengine Helicopters." This study was conducted for the U. S. Army Aviation Materiel Laboratories (USAAVLABS) under contract DAAJ02-67-C-0009 between 2 December 1966 and 15 July 1967.

USAAVLABS technical direction was provided by Mr. P. Chesser and Mr. R. Furgurson, with Mr. R. M. Swick serving as the Allison project engineer. The principal investigators at Allison were C. A. Skarvan and W. K. Kimmel.

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LIST OF SYMBOLS

CDP, P_c	Compressor discharge pressure	Pounds per square inch absolute or pounds per inch of mercury absolute
CIT	Compressor inlet temperature	Degrees Fahrenheit or degrees Rankine
GP	Gas producer section of engine	
GPL	Gas producer lever angle	Degrees
I_{PT}	Mass polar moment of inertia of power turbine	Pound-feet ² or slug-feet ²
I_r	Mass polar moment of inertia of helicopter rotor	Pound-feet ² or slug-feet ²
I_s	Mass polar moment of inertia of power turbine and transmission	Pound-feet ² or slug-feet ²
I_{TRANS}	Mass polar moment of inertia of transmission	Pounds-feet ² or slug-feet ²
K_b	Engine transfer function gain torque to fuel flow	Pound-foot per pound per hour
K_c	Gas producer reset governor gain, speed request reset to actual speed	Revolutions per minute per revolutions per minute
K_e	Gas producer gain, speed to fuel flow	Revolutions per minute per pound per hour
K_g	Gas producer governor gain, fuel flow/compressor discharge pressure to speed or fuel flow to speed	Pounds per hour per inch of mercury absolute per revolutions per minute, or pounds per hour per revolutions per minute

K_i	Power turbine governor integral gain, rate of change of speed request to speed error	Revolutions per minute per second per revolutions per minute
K_L	Helicopter load gain	Pound-foot per revolutions per minute
K_m	Helicopter mast shaft stiffness	Pound-foot/radian
K_p	Governor proportional gain, fuel flow to compressor discharge pressure or fuel flow to speed	Pounds per hour per inch of mercury absolute per revolutions per minute, or pounds per hour per revolutions per minute
K_r	Power turbine governor reset gain speed request to actual speed	Revolutions per minute per revolutions per minute
K_t	Governor proportional gain, fuel flow/compressor discharge pressure to speed or fuel flow to speed	Pounds per hour per inch of mercury absolute per revolutions per minute, or pounds per hour per revolutions per minute
K_{TM}	Engine torquemeter shaft stiffness	Pound-foot/radian
N_1, N_{gp}	Gas producer speed	Percent design speed or revolutions per minute
N_2, N_{PT}	Power turbine speed	Percent design speed or revolutions per minute
N_r, N_R	Helicopter rotor speed	Percent design speed or revolutions per minute
N_s	Helicopter transmission output shaft speed	Percent design speed or revolutions per minute
N_{se}	Power turbine speed error	Percent design speed or revolutions per minute

P/L	Power lever angle	Degrees
$P_{N_{PT}}$	Pressure proportional to engine power turbine speed	Inches of mercury absolute
P_o	Ambient pressure	Inches of mercury absolute
P_Q	Pressure proportional to engine torque	Inches of mercury absolute
P_r	Regulator pressure	Inches of mercury absolute
PT	Power turbine section of engine	—
PTL	Power turbine lever angle	—
P_x	Nonregulated pressure	Inches of mercury absolute
Q	Torque	Pound-foot
Q_{REF}	Torque reference signal	(Depends on signal source)
S	Laplace operator	—
SHP	Shaft horsepower	Horsepower
TOT	Gas producer turbine outlet temperature	Degrees Fahrenheit or degrees Rankine
W_f	Fuel flow	Pounds per hour
$\frac{W_f}{CDP}, \frac{W_f}{P_c}$	Fuel flow/compressor discharge pressure	Pounds per hour per inch of mercury absolute, or pounds per hour per pound per square inch absolute
ω_n	Undamped natural frequency of power turbine and rotor on flexible shaft	Radians per second
ω_r	Natural frequency of rotor drive system	Radians per second

τ_B	Engine lag time constant	Second
τ_E, τ_e	Engine gas producer lag time constant	Second
τ_L	Load lag time constant	Second
τ_Q	Load sharing control lag time constant	Second
τ_r	Power turbine governor reset lag time constant	Second
τ_S	PT speed sense lag time constant	Second
τ_2	Metering valve lag time constant	Second
τ_1	Power turbine governor lag time constant	Second
τ_3	Gas producer speed sense lag time constant	Second
ζ_r	Helicopter rotor damping ratio	—
ζ_n	Power turbine damping ratio	—
Δ	Incremental change	—

INTRODUCTION

Previously conducted investigations have shown that the multiengine helicopter configuration presents unique engine control problems. The operational requirements of the multiengine helicopter dictate that the engine controls provide automatic engine and rotor speed governing, automatic engine power matching, and automatic power recovery with power loss of one or more engines.

The requirements of the governing system in the multiengine helicopter are diversified and challenging. This is due to the large power range over which the engines are operated, the changing load system inertia with different modes of operation (decoupled rotor during autorotation, an engine shut down, normal operation), and the resilient shafting of the helicopter rotor system.

When the output shaft of free turbine engines in a multiengine system is mechanically coupled to a single load system, all power turbines operate at identical speeds. The engine control systems cannot be allowed to operate independently if load sharing between the engines is to be maintained.

In the event of an engine malfunction (power loss) during a critical flight mode, early detection of the malfunction and selection of emergency power operation is required to allow safe continuation of aircraft operation. The delay of the pilot in the detection of the failure and the selection of emergency power operation would be appreciable, especially in a critical flight maneuver. Automatic power recovery and control is required for this condition.

This report describes the results of a study program conducted to determine and define the design requirements of an optimum, coordinated, multiengine control system. The program was directed toward the utilization of proven concepts and principles for gas turbine engine control, enabling conversion of the selected design to functional hardware with minimum research and development effort. This program included two-, three-, and four-engine systems.

EVALUATION OF POWER TURBINE GOVERNING MODES

This evaluation was directed toward determining the optimum power turbine governing mode for a helicopter gas turbine engine. The requirements of the governing system in the helicopter application are diversified and challenging because of the nature of the load system. The significant requirements are as follows:

- Accurate control (governing) of the rotor speed over the load range from zero to maximum
- Stable governing of the high inertia rotor system over the full load range
- Stable governing with the resilient shaft drive system by not supporting torsional excitations
- Rapid engine power transient response to load changes minimizing the transient overspeed and underspeed
- Stable governing of the low inertia power turbine when decoupled from the rotor system

Of these requirements, those relating to stability are the most challenging. Therefore, the major criterion in the governing mode evaluation was stability. This evaluation has resulted in the conclusion that a proportional power turbine governor with a lagged gain reset (feedback) is the desirable mode. Stability, transient response, and governing accuracy studies have indicated that this approach will meet the significant requirements when employed with collective lever-power turbine lever coordination to trim out the steady-state speed droop. Figure 1 is a functional diagram of the governing mode selected—a gas producer control employing compressor discharge pressure.

It was indicated that two modes, using lagged gain reset, were satisfactory; i. e., one where the fuel scheduling is compressor discharge pressure compensated, and one where it is not. The final selection for an engine is dependent on the specific air pressure compensating parameter employed in the gas producer control.

The following paragraphs present a summary of the analyses that were conducted, resulting in the selection of the lagged gain reset mode.

GOVERNOR MODES EVALUATED

The governor mode evaluation was purposely limited to concepts and principles that have been previously employed in gas turbine engine controls. This was done to provide assurance that the results of this evaluation would be practical and useful. Concepts employing frequency band

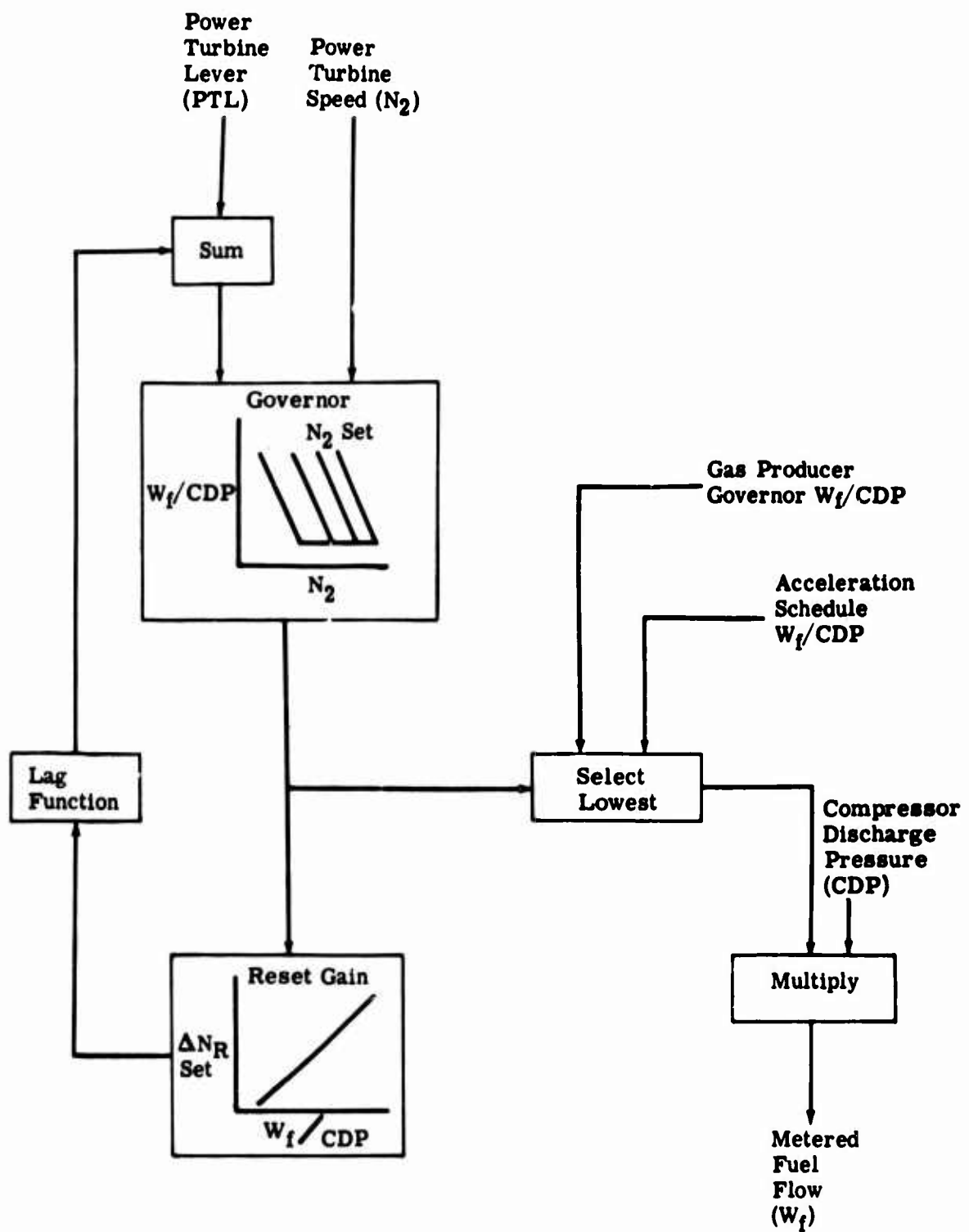


Figure 1. Functional Diagram of Power Turbine Governing Concept.

filters, multiple lead-lag functions, and tuning circuits have been excluded from this evaluation as being risk concepts with regard to the helicopter application, requiring further research and development efforts before they can be considered applicable.

The following seven different power turbine speed governing modes were included in this evaluation:

- Direct fuel flow/compressor discharge pressure governor with lagged gain reset
- Direct fuel flow governor with lagged gain reset
- Direct fuel flow governor
- Direct fuel flow/compressor discharge pressure governor
- Gas producer fuel flow governor reset
- Gas producer fuel flow/compressor discharge pressure governor reset
- Direct fuel flow/compressor discharge pressure governor with integral reset

These modes are more specifically defined in the following paragraphs.

Direct Fuel Flow/Compressor Discharge Pressure Governor With Lagged Gain Reset

This mode consists of a proportional fuel governor with a reset function operating through a time lag. The reset is accomplished by utilizing the governor output signal as a feedback signal to vary the governor speed setting. A time lag is employed in the reset or feedback loop to provide a governor action that is dynamically different from steady state. The result is that a dynamic gain can be provided that is lower than the steady-state gain. A compressor discharge pressure signal is also employed to affect the fuel scheduling action of the power turbine governor, providing a variable gain as a function of the gas producer speed.

Direct Fuel Flow Governor With Lagged Gain Reset

This mode is similar to the direct fuel flow/compressor discharge pressure governor with lagged gain reset, but without the compressor discharge pressure bias. This mode would utilize a compressor inlet pressure bias.

Direct Fuel Flow Governor

This is a conventional proportional governor design which varies the fuel flow as a function of the sensed speed and a governor speed reference

setting. Altitude pressure compensation may be employed with this governing mode, but no other variables would be involved in the power turbine governor operation.

Direct Fuel Flow/Compressor Discharge Pressure Governor

This mode is the same as the direct fuel flow governor except for the added compressor discharge pressure bias. In this case, the fuel flow, during power turbine governing, would also be a function of the engine parameter compressor discharge pressure. This effectively provides a variable dynamic gain of the governor because the compressor discharge pressure is a function of the gas producer speed.

Gas Producer Fuel Flow Governor Reset

The power turbine governor would be a proportional design with its generated signal employed to vary the speed setting of the gas producer governor. As a result, the fuel flow during power turbine governing is also affected by the gas producer speed.

Gas Producer Fuel Flow/Compressor Discharge Pressure Governor Reset

This mode is the same as the gas producer fuel flow governor reset except for the added compressor discharge pressure bias. This engine pressure would be employed in the gas producer control to bias the gas producer governor effect on fuel flow.

Direct Fuel Flow/Compressor Discharge Pressure Governor With Integral Reset

This is a proportional-plus-integral governor with compressor discharge pressure compensation of the metered fuel flow. The proportional function is similar to that of the direct fuel flow/compressor discharge pressure governor. The integrator action varies the fuel flow until zero speed error is achieved, with the rate of this action established by the integrator gain and the magnitude of the speed error.

STABILITY ANALYSIS

Past experience with smaller helicopter powerplant designs has confirmed the necessity for careful analysis of the engine-control-rotor system with regard to torsional stability. The rotating portion of a turbine powered helicopter consists of several inertial loads connected with shafts having some torsional resilience. The main rotor system may be represented as shown in Figure 2.

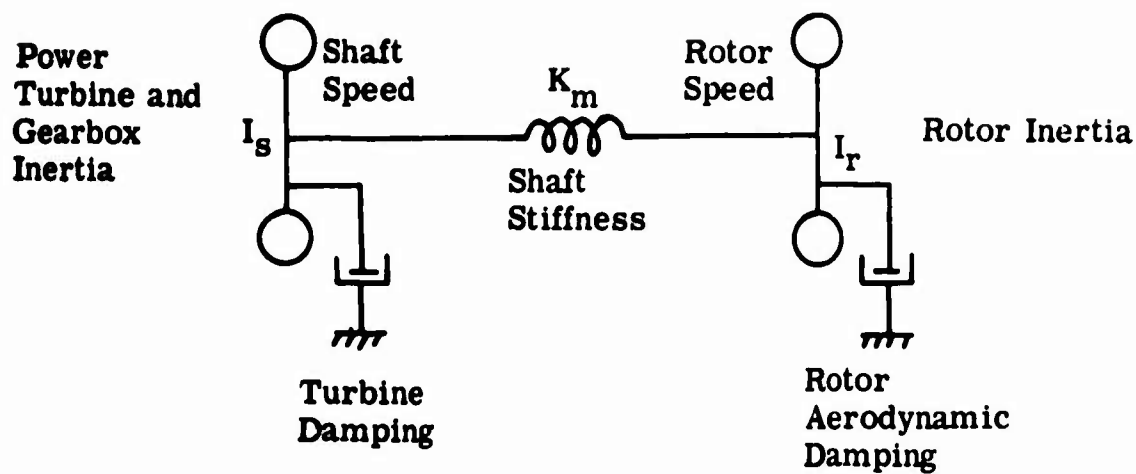


Figure 2. Main Rotor System.

In general, engine output shaft speed is sensed by the fuel control power turbine governor, which adjusts fuel flow to maintain the desired speed. However, the power turbine-mast rotor combination forms a highly underdamped system (damping factor ≈ 0.05) which oscillates at a natural frequency between 2 and 5 cps for large helicopters. If the gain and dynamics

of the engine and fuel control cause sufficient phase shift to reinforce these torsional oscillations, they may become divergent, resulting in physical damage to the helicopter. The design of an engine-control-rotor system which has sufficient margin to eliminate or minimize the problem of load resonance or torsionals is a compromise and depends on the following variables:

- Rotor mast stiffness
- Power turbine and gearbox polar moment of inertia
- Rotor polar moment of inertia
- Power turbine governor mode
- Steady-state speed droop requirements
- Fuel control dynamic characteristics
- Engine gains and dynamics
- Inherent helicopter structural damping

A comparative evaluation of various power turbine governing modes was made giving consideration to governing stability, torsional stability, transient response, and steady-state governing accuracy (speed droop) over the zero-to-maximum power range. This evaluation was based on a single-engine powered system with the helicopter rotor parameters (mast shaft stiffness and polar moment of inertia) scaled down accordingly.

A linearized analog computer simulation of the engine, power turbine governor, and helicopter rotor system was formulated to investigate torsional and governing stability characteristics with each of the different potential governing modes. A block diagram defining the analog computer simulation is shown in Figure 3. Each mode was investigated at high power (100-percent SHP), low power (7-percent SHP), and zero power (decoupled rotor) conditions, covering the full operating regime.

A Bode analysis of the engine-control-rotor system was also made for the various control modes. This was done to gain a better understanding of the system dynamic characteristics and to determine the superior modes. A Bode analysis provides a convenient means of evaluating the torsional gain margin and the low frequency phase margin. The torsional gain margin, determined in decibels, is a measure of torsional stability, since it indicates how much the loop gain of the system can be increased before the dynamic elements cause enough phase shift to result in a torsionally divergent system. The low frequency phase margin, determined in degrees, is a measure of the stability of the basic system governing loop. Comparing any two systems, a lower phase or gain margin indicates that the system will be more oscillatory and will take longer to stabilize following a disturbance. Negative gain or phase margins imply an unstable (divergent) system.

In analyzing the system transient response, a torsional gain margin of 4 to 6 decibels and a low frequency phase margin of 20 to 30 degrees were established as guidelines for the minimum acceptable stability margins

A comparative evaluation of the various power turbine governor modes (Table I) indicates that either the direct fuel flow with lagged gain reset or fuel flow/compressor discharge pressure with lagged gain reset provides the most desirable system, with respect to both torsional and basic governing stability and assuming a governor gain requirement of 5-percent speed droop. Satisfactory performance is maintained at high power, low power, and decoupled rotor conditions.

The relative stability margins of the different modes for high power, low power, and decoupled rotor operation are also summarized in Table I.

Description of Analytical Model

A linearized equivalent of the Allison 501-M34 engine was represented on the analog computer using the following equations:

$$\Delta N_1 = K_e \Delta W_f / (1 + \tau_e S)$$

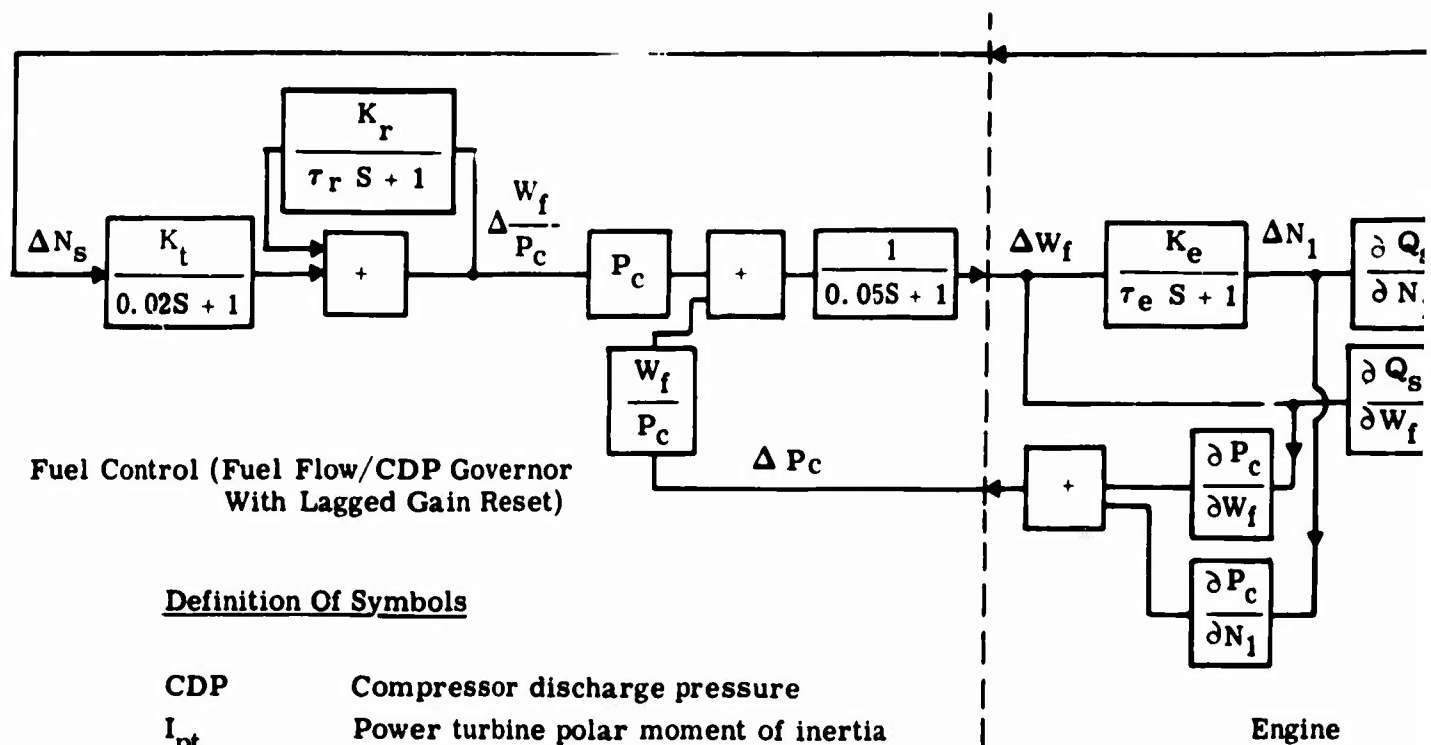
$$\Delta W_f = \frac{W_f}{CDP} \Delta CDP + CDP \Delta \frac{W_f}{CDP}$$

$$\Delta CDP = \frac{\partial CDP}{\partial W_f} \Delta W_f + \frac{\partial CDP}{\partial N_1} \Delta N_1$$

$$\Delta Q_s = \frac{\partial Q_s}{\partial W_f} \Delta W_f + \frac{\partial Q_s}{\partial N_1} \Delta N_1 + \frac{\partial Q_s}{\partial N_s} \Delta N_s$$

The rotor system dynamics were simulated by considering a simple two-mass, one-shaft system. This representation was considered to be adequate for this study because of the following:

- It reveals the basic torsional resonance phenomenon associated with turbine-powered helicopter rotor drive systems.
- This is a comparative evaluation of the different governing modes.
- Previous analog torsional stability studies have indicated that results are not significantly affected by adding tail rotor dynamics, main rotor articulation, or other computer simulation refinements.

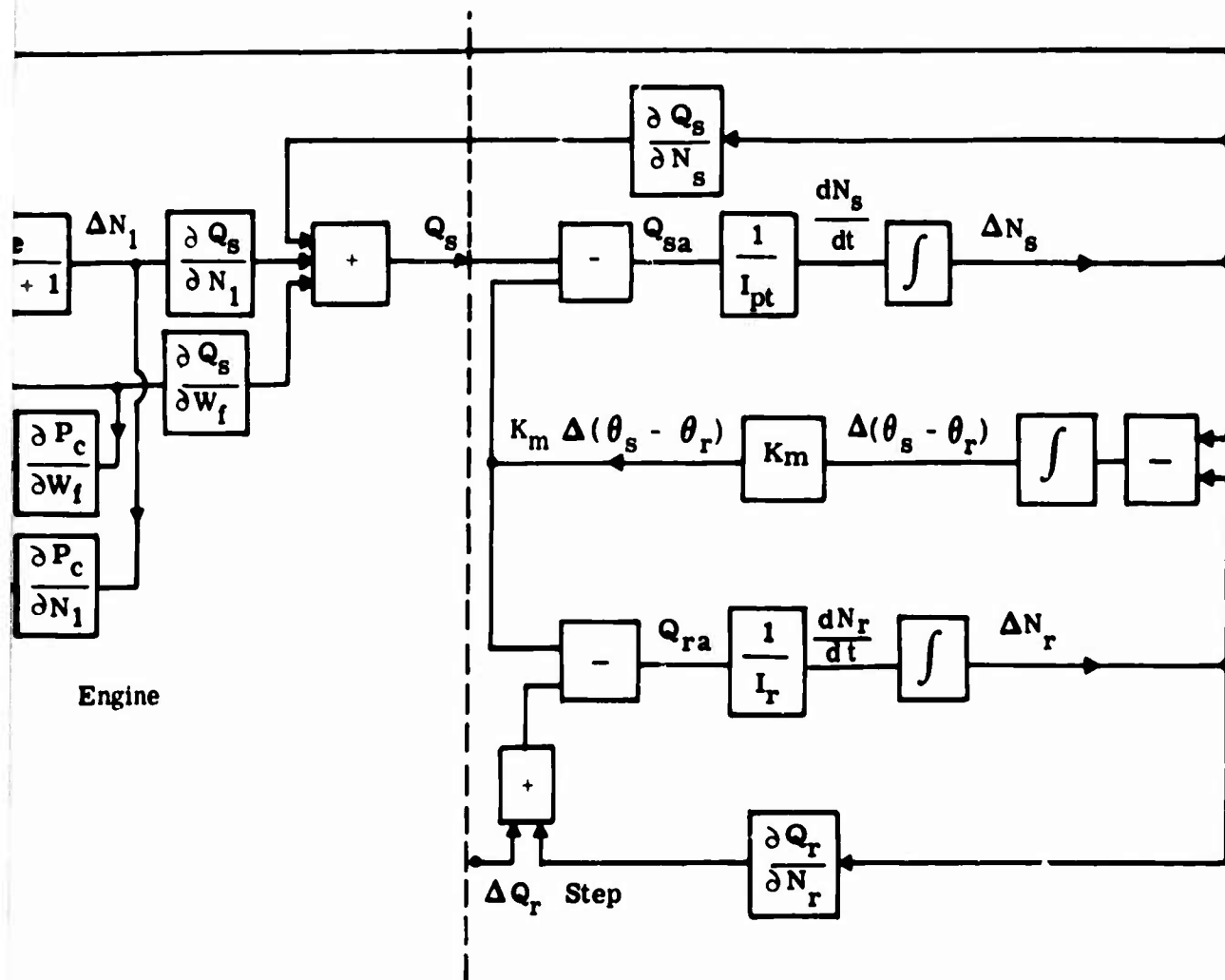


Definition Of Symbols

CDP	Compressor discharge pressure
I_{pt}	Power turbine polar moment of inertia
I_r	Main rotor polar moment of inertia
K_e	Engine gas producer gain
K_m	Rotor mast stiffness
K_r	Power turbine governor reset gain
K_t	Power turbine governor proportional gain
N_1	Engine gas producer speed
N_r	Rotor speed
N_s	Engine shaft speed
P_c	CDP as sensed by fuel control
Q_r	Rotor aerodynamic load torque
Q_{ra}	Rotor accelerating torque
Q_s	Engine shaft torque
Q_{sa}	Engine shaft accelerating torque
S	Laplace operator
W_f	Engine fuel flow rate
$\theta_s - \theta_r$	Angular twist of rotor mast
\int	Integration with respect to time
τ_e	Engine time constant
τ_r	Power turbine governor reset lag time constant
$\frac{\partial Q_s}{\partial W_f}$ (example)	Partial derivative of engine shaft (Q_s) with respect to fuel flow (W_f).

Figure 3. Analog Computer Block Diagram.

A



Rotor And Power Turbine
Speed Dynamics

B

TABLE I				
COMPARISON OF TORSIONAL AND LOW FREQUENCY STABILITY MARGINS OF VARIOUS POWER TURBINE GOVERNOR CONTROL MODES				
Power Turbine Governor Control Mode	Steady-State Speed Droop (%)	Flight Condition	Low Frequency Phase Margin (degrees)	Torsional Gain Margin (decibels)
Direct Fuel Flow/CDP Governor With Lagged Gain Reset (sec) $\tau_r = 0.2$ $K_r = 0.5$	5	High Power Low Power Decoupled Rotor	40 35 37	6.3 15.0 18.5
Direct Fuel Flow Governor With Lagged Gain Reset (sec) $\tau_r = 0.2$ $K_r = 0.5$	5	High Power Low Power Decoupled Rotor	63 41 33	9.5 9.6 12.0
Direct Fuel Flow Governor (sec) $\tau_1 = 0.5$	10	High Power Low Power Decoupled Rotor	59 28 7	7.5 7.0 2.4
Direct Fuel Flow/CDP Governor (sec) $\tau_1 = 0.5$	10	High Power Low Power Decoupled Rotor	22 28 11	6.5 14.3 4.7
Gas Producer Fuel Flow Governor Reset Mode (sec) $\tau_1 = 2.0$	10	High Power Low Power Decoupled Rotor	68 43 54	8.5 7.0 11.0
Gas Producer Fuel Flow/CDP Governor Reset Mode (sec) $\tau_1 = 2.0$	10	High Power Low Power Decoupled Rotor	66 38 37	6.0 14.0 10.8
Direct Fuel Flow/CDP Governor With Integral Reset (sec) $\tau_1 = 0.5$ $K_I = 0.1^{-1}$	15	High Power Low Power Decoupled Rotor	27 33 20	10.5 20.0 8.5

Based on information obtained from helicopter manufacturers, a main rotor inertia of 33,500 slug-square feet per engine (at 150 rpm) was selected as being representative of helicopters in the 5000-horsepower power class. The range of effective rotor mast shaft stiffness investigated covered main rotor natural frequencies ranging from 2 to 6 cycles per second. This range was representative of helicopters in this power class.

To make a Bode analysis of this system, the transfer functions of the individual elements had to be derived and evaluated. The rotor-shaft-power turbine transfer function was derived by first writing Newton's equations of motion for the two-mass, one-shaft system, utilizing Laplace notation. By algebraic manipulation, the desired transfer function becomes

$$\frac{\Delta N_s(S)}{\Delta Q_s(S)} = \frac{K_L \left(\frac{1}{\omega_r^2} S^2 + \frac{2\zeta_r}{\omega_r} S + 1 \right)}{(\tau_L S + 1) \left(\frac{1}{\omega_n^2} S^2 + \frac{2\zeta_n}{\omega_n} S + 1 \right)}$$

All the constants in this equation are functions of the rotor mast shaft stiffness, the two inertias, engine damping, and rotor aerodynamic damping.

Similarly, the engine transfer function is

$$\frac{\Delta Q_s(S)}{\Delta W_f(S)} = \frac{K_b (\tau_B S + 1)}{(\tau_e S + 1)}$$

Transfer functions for each of the power turbine governing modes were derived in the form $\Delta W_f / \Delta N_s$. For example, the fuel flow/compressor discharge pressure with lagged gain reset governor transfer function is

$$\frac{\Delta W_f(S)}{\Delta N_s(S)} = \frac{C_1 (\tau_r S + 1) (\tau_e S + 1)}{(\tau_L S + 1) \left(\frac{\tau_r}{1-K_r} S + 1 \right) (C S^2 + D S + 1)}$$

All the constants in these equations can be evaluated from engine performance data, control gains, and time constants.

The over all system transfer function can then be evaluated by multiplying the individual transfer functions of the control, engine, and rotor systems—

$$\frac{\Delta N (S)}{\Delta N_s (S)} = \underbrace{\frac{\Delta W_f}{\Delta N_s}}_{\text{Control}} \cdot \underbrace{\frac{\Delta Q_s}{\Delta W_f}}_{\text{Engine}} \cdot \underbrace{\frac{\Delta N_s}{\Delta Q_s}}_{\text{Rotor}}$$

A Bode analysis of this transfer function defines the governing stability characteristics of the system in terms of gain margin, phase margin, and system frequency.

Direct Fuel Flow/Compressor Discharge Pressure With Lagged Gain Reset

The basic block diagram defining this mode of control is shown in Figure 4.

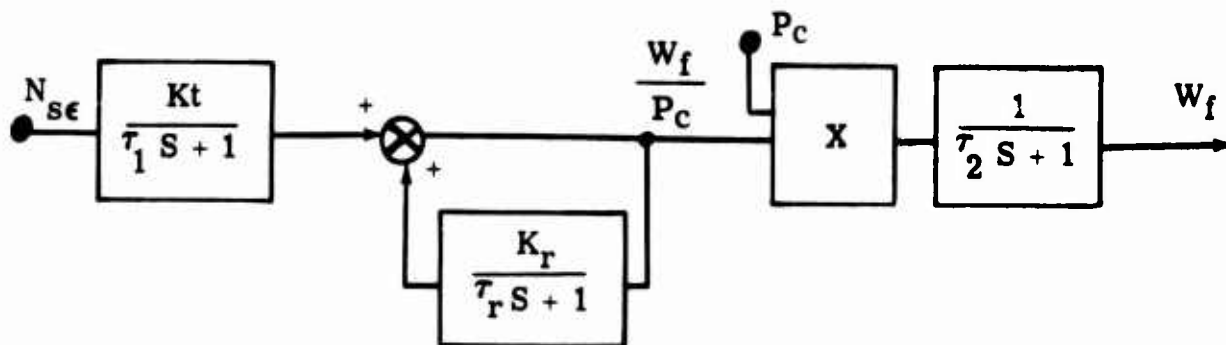


Figure 4. Direct Fuel Flow/Compressor Discharge Pressure With Lagged Gain Reset Block Diagram.

Where:

- N_{se} = Engine speed error ($N_{Actual} - N_{Set}$)
- K_t = Governor proportional gain, pounds per hour per inches of mercury/rpm
- K_r = Governor reset gain
- τ_r = Governor reset time constant

- τ_1 = Power turbine governor lag
- τ_2 = Metering valve control lag
- P_c = Compressor discharge pressure as sensed by the fuel control
- W_f = Fuel flow

This mode of control is basically a direct W_f/P_c power turbine governor with a lagged $W_f/P_c \times K_r$ signal adding back in as a positive feedback. The positive feedback results in the steady-state governor's gain being increased to $K_t/(1-K_r)$. The transfer function for this mode is

$$\frac{\Delta(W_f/P_c)(S)}{\Delta N_s(S)} = \frac{[K_t/(1 - K_r)] (\tau_r S + 1)}{[\tau_r/(1 - K_r)]S + 1}$$

The lagged reset action provides a lower effective gain at higher input frequencies, while providing a steady-state gain of $K_t/(1-K_r)$. For example, using a reset gain of 0.5, the dynamic gain can be reduced to nearly 50 percent of the steady-state gain. This dynamic gain difference tends to improve the problem of load resonance or torsionals, since the effective loop gain is reduced at the torsional frequency.

Results of this analysis indicate that this mode of control provides a satisfactory system at high power, low power, and decoupled rotor conditions. The Bode analysis in Table II indicates the torsional gain margins, assuming a reset gain of 0.5, a reset time constant of 0.2 second, and a steady-state speed droop of 5 percent.

TABLE II		
BODE ANALYSIS		
(0.5-Reset Gain, 0.2-Second Reset Time Constant, and 5-Percent Steady-State Droop)		
Flight Condition	Low Frequency Phase Margin (Degrees)	Torsional Gain Margin (Decibels)
High Power	40	6.3
Low Power	35	15.0
Decoupled Rotor	37	18.5

The system Bode plots and the analog simulation response traces for these three power conditions are shown in Figures 5, 6, and 7.

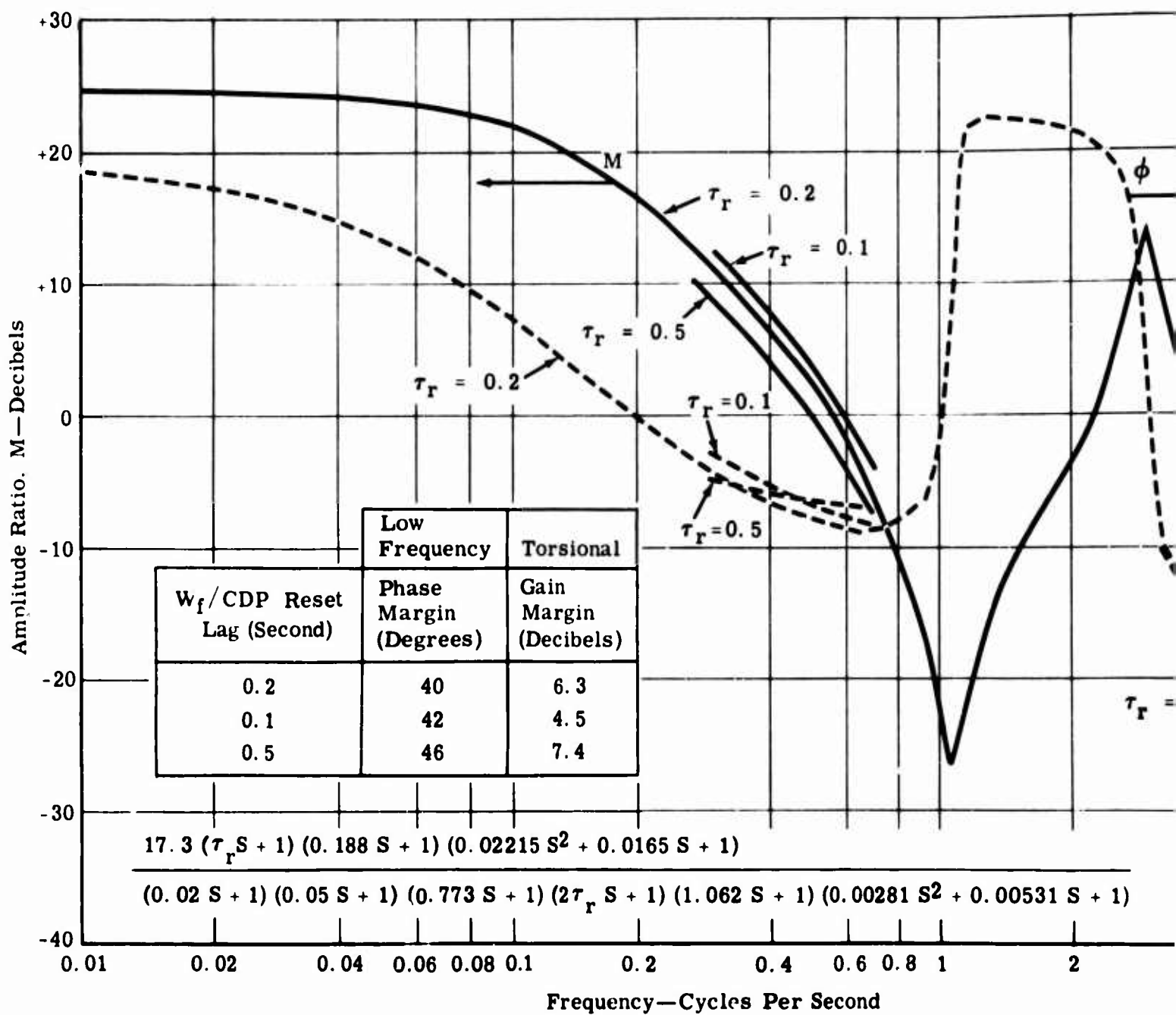
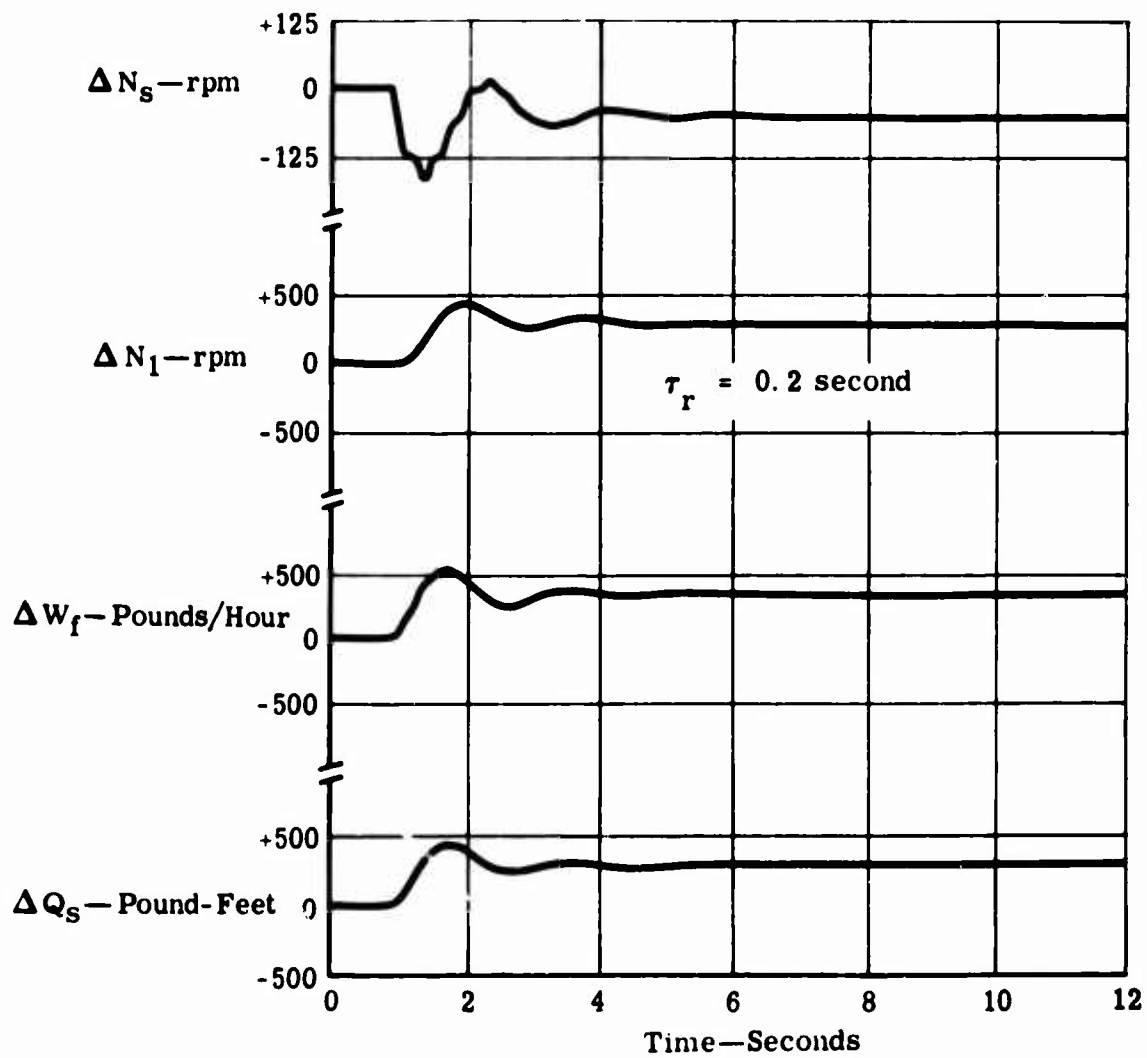
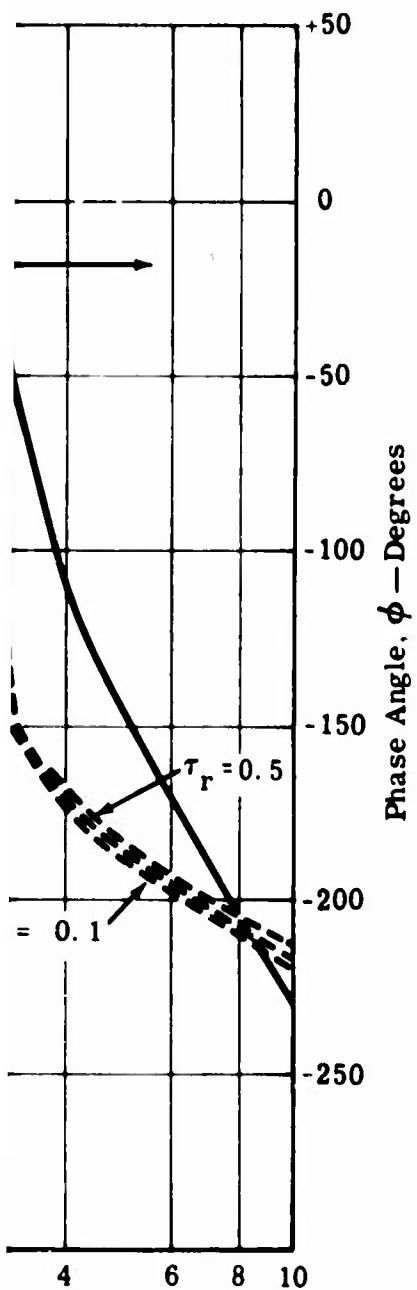


Figure 5. Fuel Flow/Compressor Discharge Pressure Governor With Lagged Gain Reset, High Power—5-Percent Droop Governor.

A



13

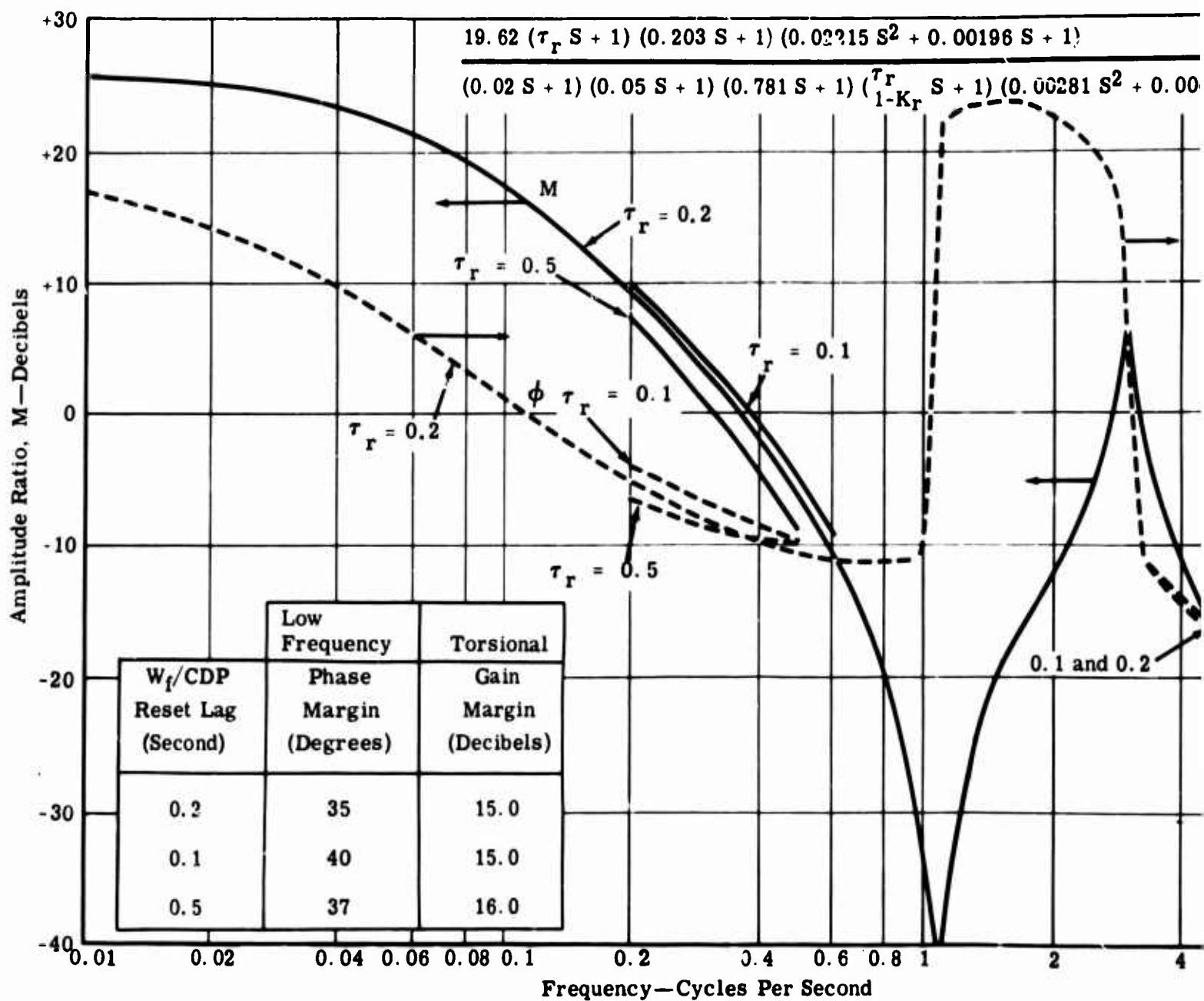
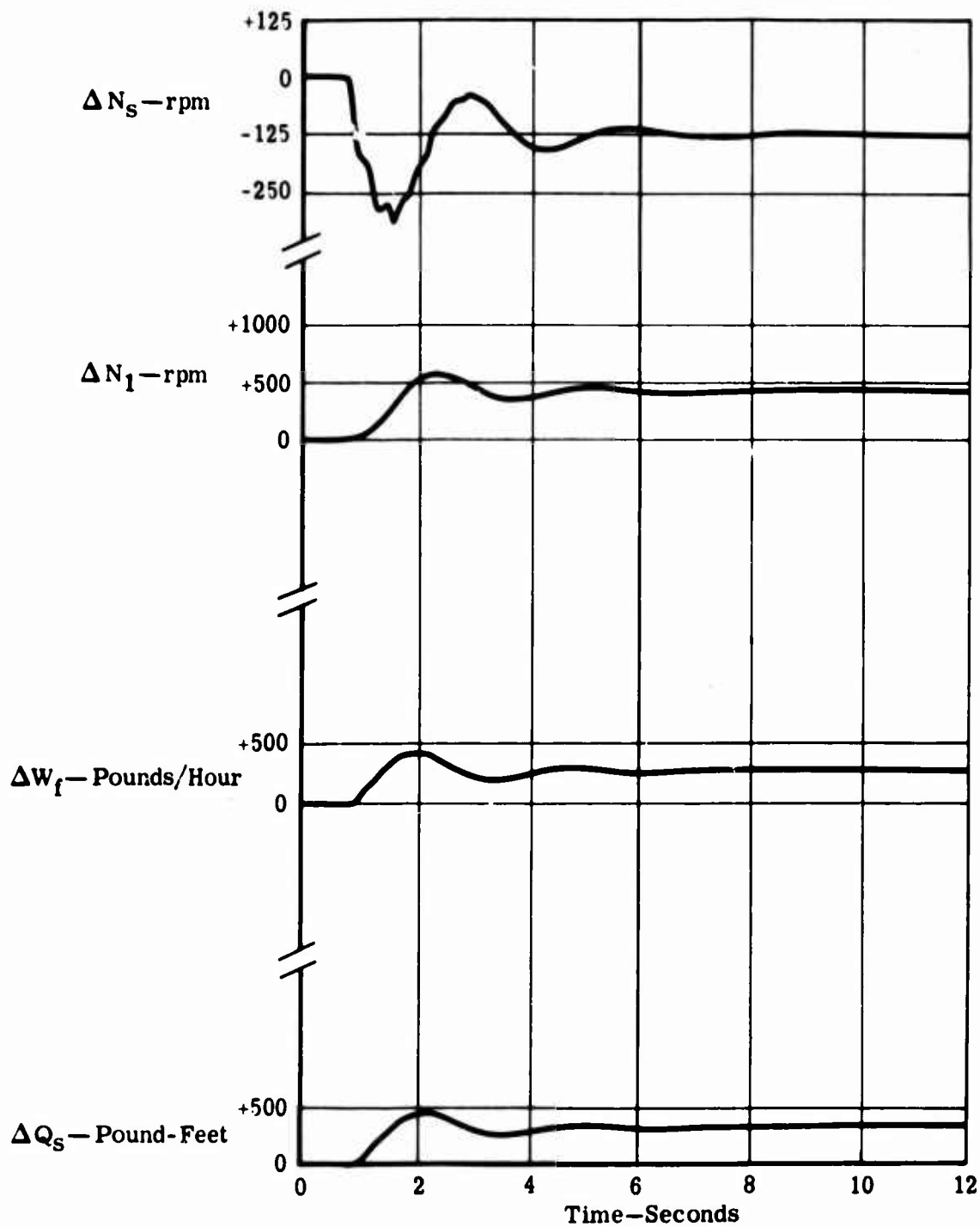
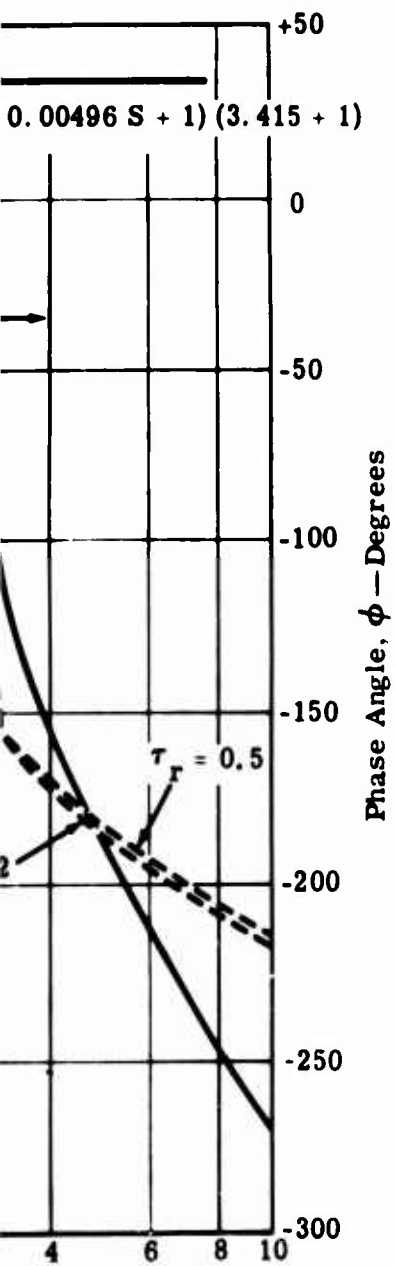


Figure 6. Fuel Flow/Compressor Discharge Pressure Governor With Lagged Gain Reset, Low Power—5-Percent Droop Governor.

A



B

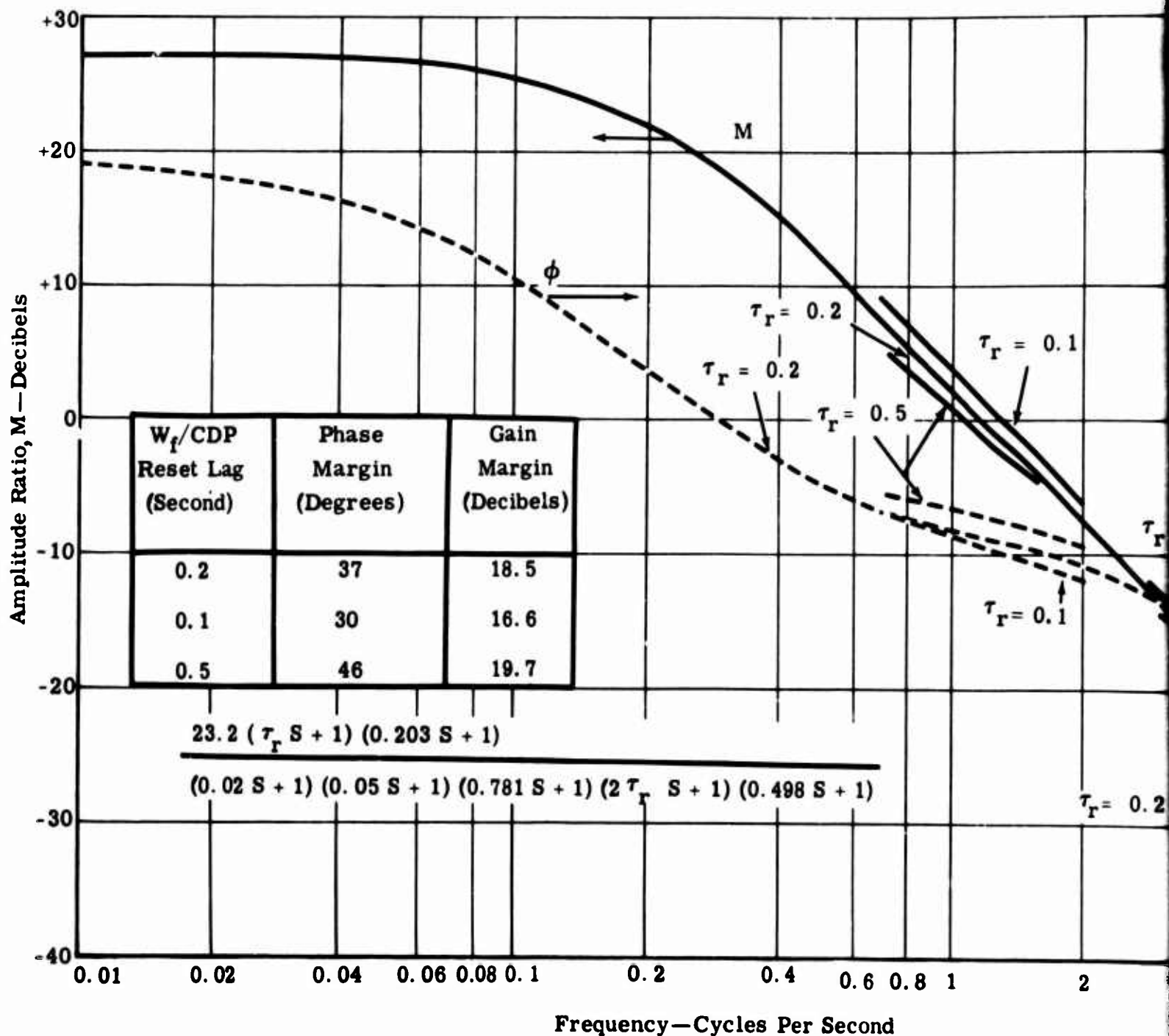
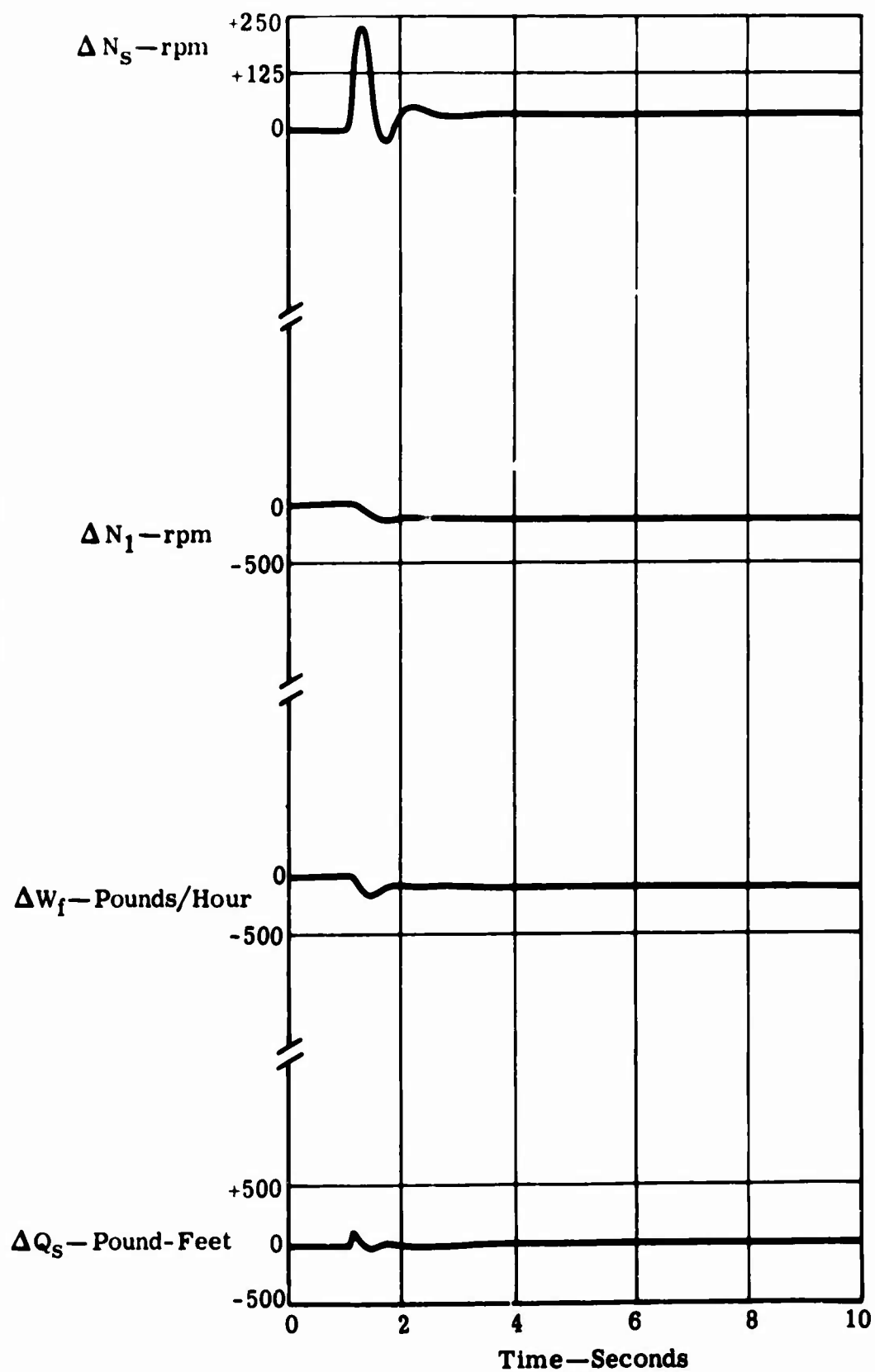
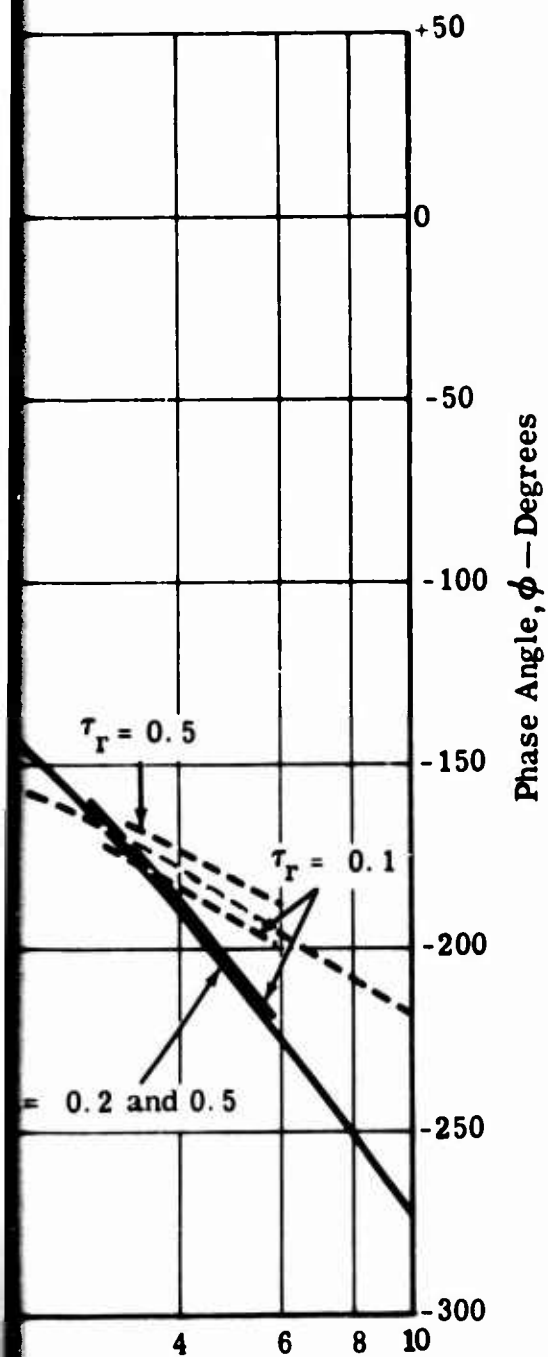


Figure 7. Fuel Flow/Compressor Discharge Pressure Governor With Lagged Gain Reset, Low Power-Decoupled Rotor—5-Percent Droop Governor.

A



B

The stability and response characteristics at all these conditions were considered satisfactory since they were free of any objectionable torsional oscillations and stabilized after 2 to 3 cycles in a reasonable length of time (4 to 6 seconds). These Bode plots also indicate that the magnitude of the reset time constant, τ_r , is not very critical as long as it is above about 0.2 second. Too large values of τ_r would tend to increase the torsional gain margin and reduce the crossover frequency (frequency at zero decibels), slowing down the system response and resulting in longer stabilization times following a disturbance.

Direct Fuel Flow Governor With Lagged Gain Reset

The diagram defining this mode of control is shown in Figure 8.

This mode of control is identical to the W_f /CDP lagged gain reset mode. However, this mode utilizes W_f rather than W_f /CDP as the control parameter. The complete transfer function for this mode of control is

$$\frac{\Delta W_f(S)}{\Delta N_s(S)} = \frac{[K_t/(1 - K_r)] (\tau_r S + 1)}{[\tau_r/(1 - K_r)] S + 1}$$

where K_t now represents the governor proportional gain expressed in pounds per hour/rpm. The analysis indicated that this mode of control also provides a satisfactory system at high power, low power, and decoupled rotor conditions. The Bode analysis in Table III shows the torsional gain and low frequency phase margins at the given flight conditions, based on a reset gain of 0.5 and a reset lag of 0.2 second.

TABLE III		
BODE ANALYSIS		
(0.5-Reset Gain and 0.2-Second Reset Lag)		
Flight Condition	Low Frequency Phase Margin (Degrees)	Torsional Gain Margin (Decibels)
High Power	63	9.5
Low Power	41	9.6
Decoupled Rotor	33	12.0

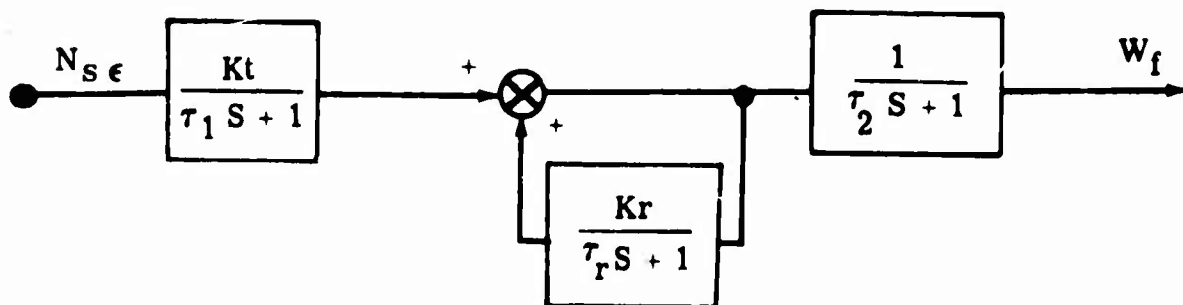


Figure 8. Direct Fuel Flow Governor With Lagged Gain Reset Block Diagram.

The system Bode plots and the corresponding analog simulation response traces for these three power conditions are shown by Figures 9, 10, and 11, respectively.

Direct Fuel Flow Governor

The basic block diagram defining this mode of control is shown in Figure 12. K_p equals the governor proportional gain in pounds per hour per rpm

This mode of control is a simple proportional power turbine governor in which the output fuel flow is proportional to the engine speed error. The dynamic characteristics of the engine-control-rotor system with this mode are such that at high power with a 5-percent speed droop governor, the governor lag (τ_1) must be increased to 0.5 second to result in a torsionally stable system. This amount of governor lag results in decoupled rotor instability (gain margin equals -3.6 decibels). Therefore, the governor gain had to be reduced to correspond to a 10-percent droop governor to enable this mode of control to be convergent at all flight conditions. A 10-percent governor with a governor lag of 0.5 second results in the stability margins presented in Table IV.

This reduced governor gain provides only 7 degrees phase margin at low power decoupled rotor conditions and is not acceptable. The governor droop would have to be increased to at least 15 percent to provide sufficient phase margin at this flight condition.

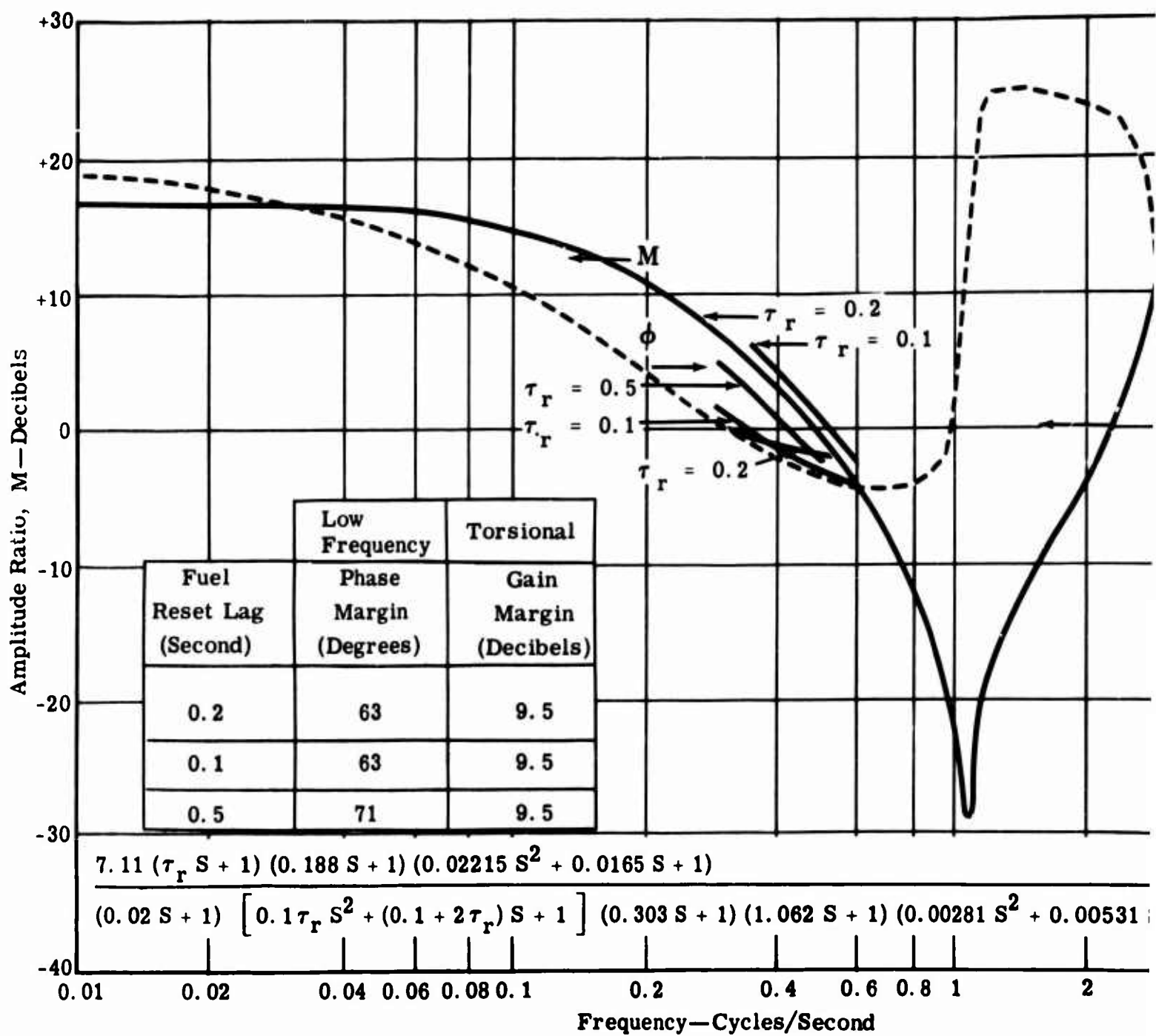
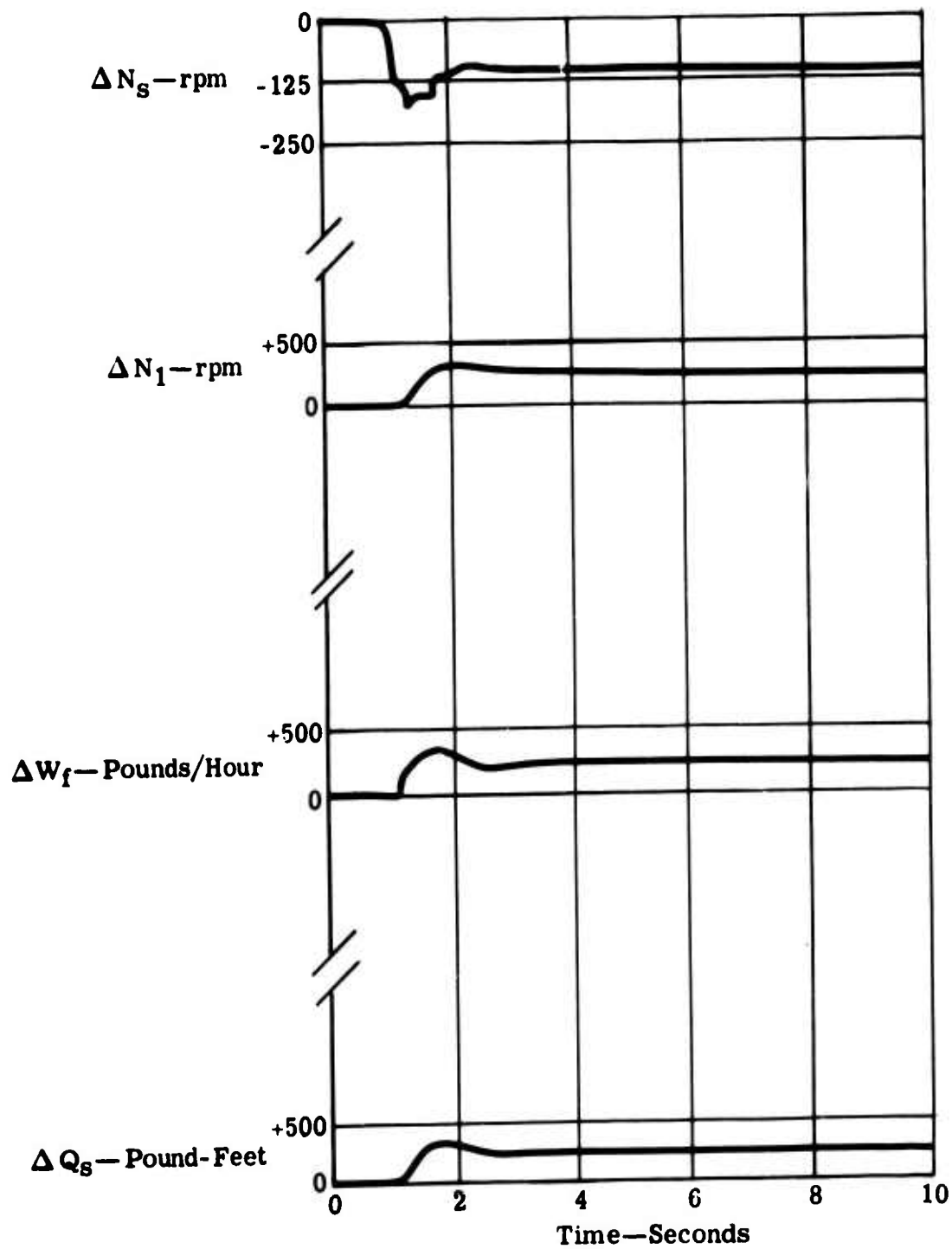
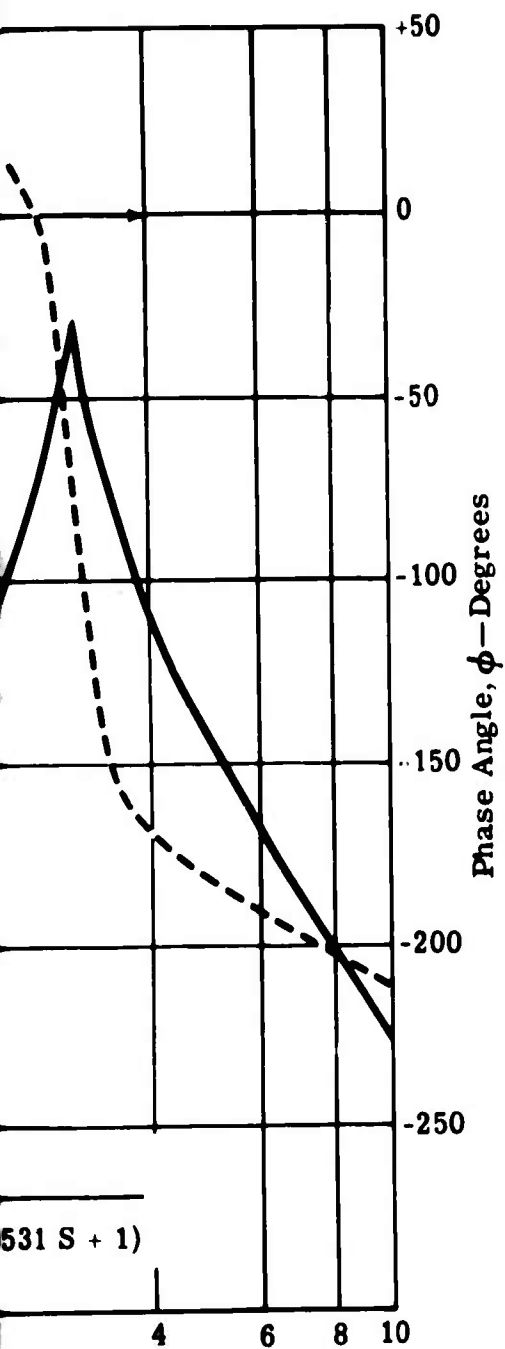


Figure 9. Fuel Flow Governor With Lagged Gain Reset, High Power—5-Percent Droop Governor.

A



B

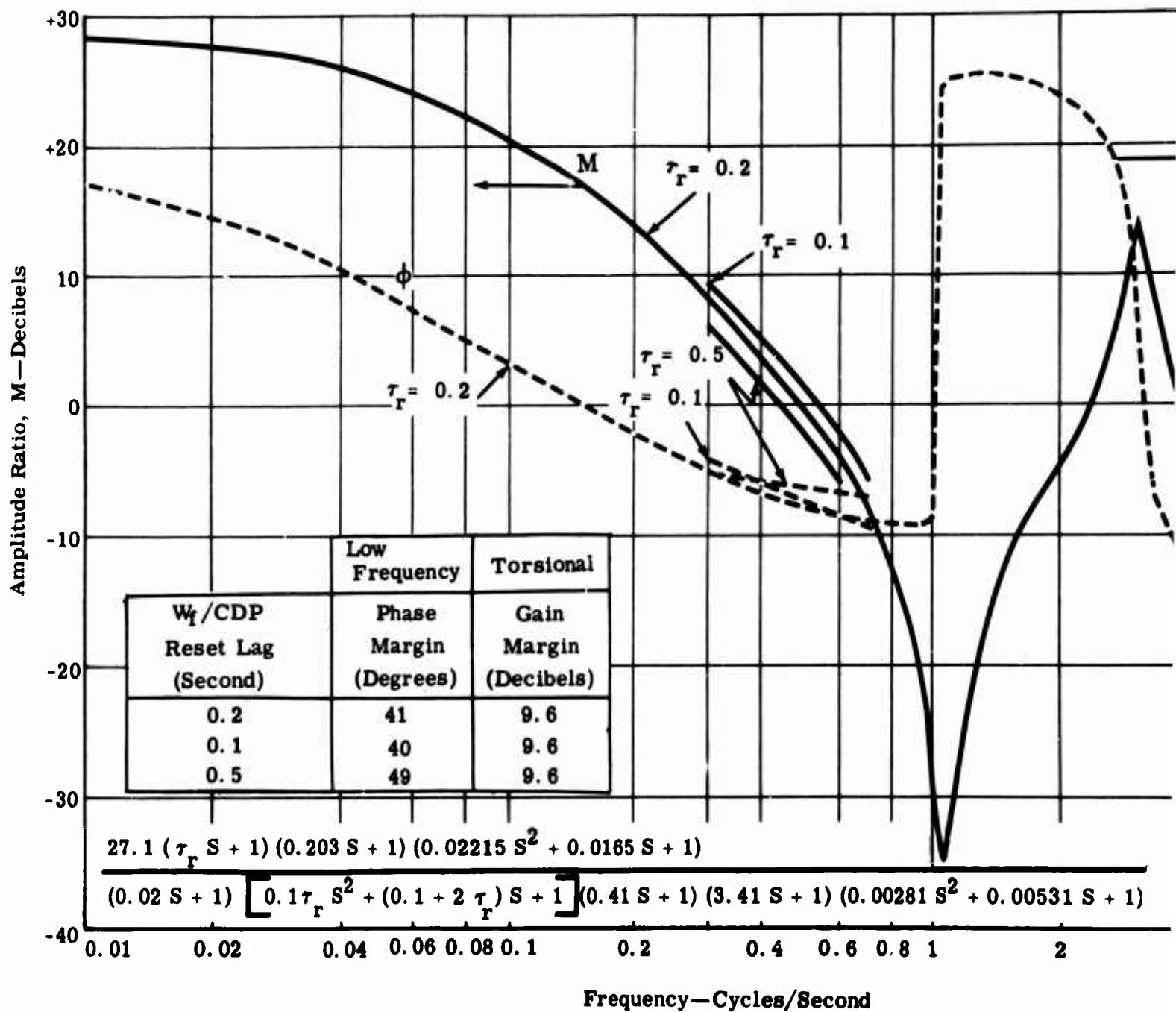
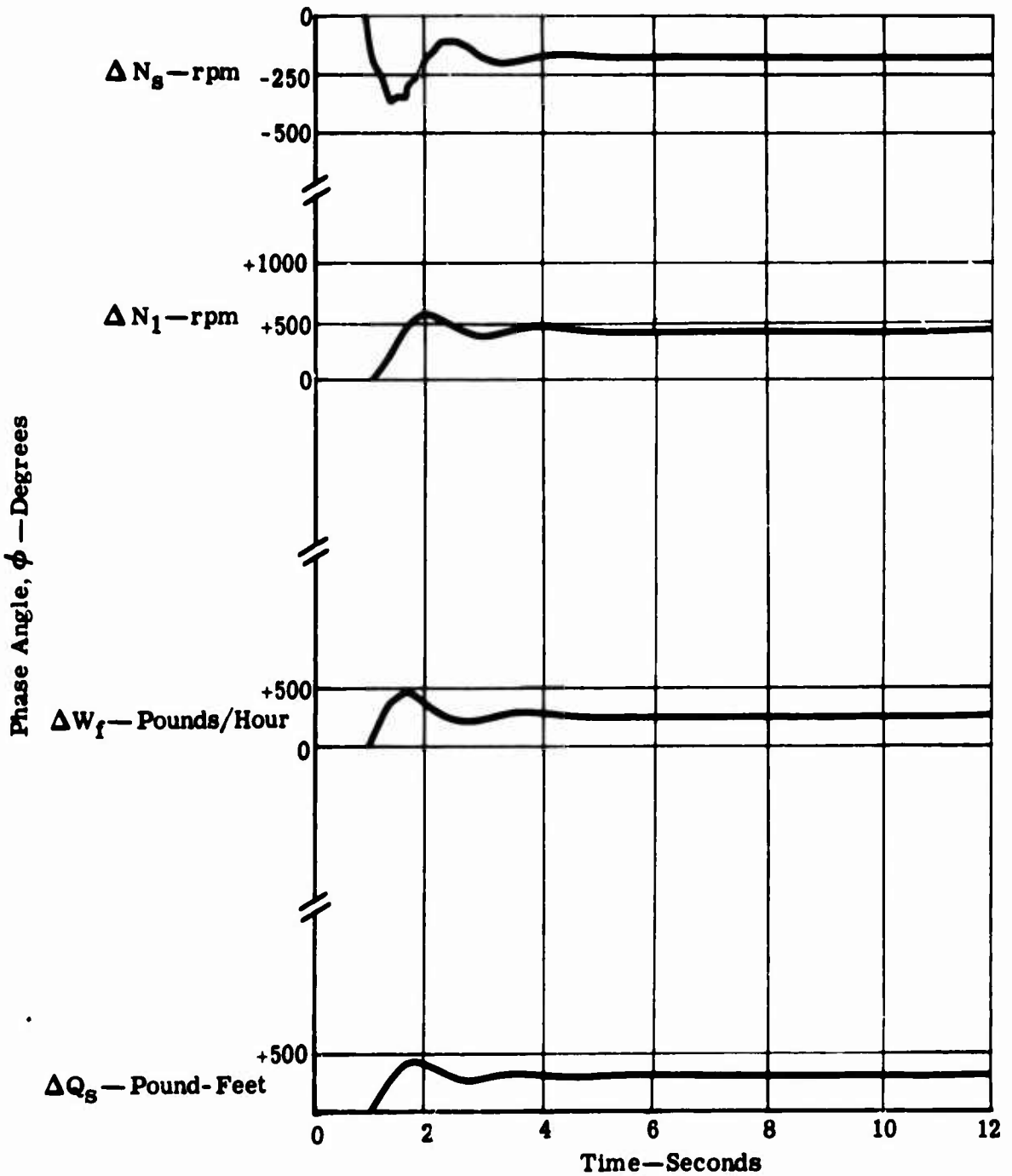
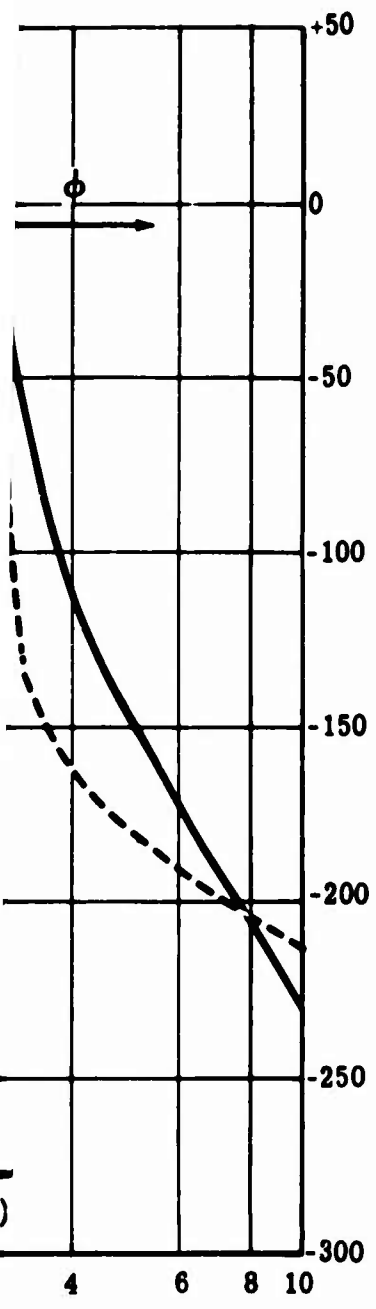


Figure 10. Fuel Flow Governor With Lagged Gain Reset, Low Power—5-Percent Droop Governor.

A



B

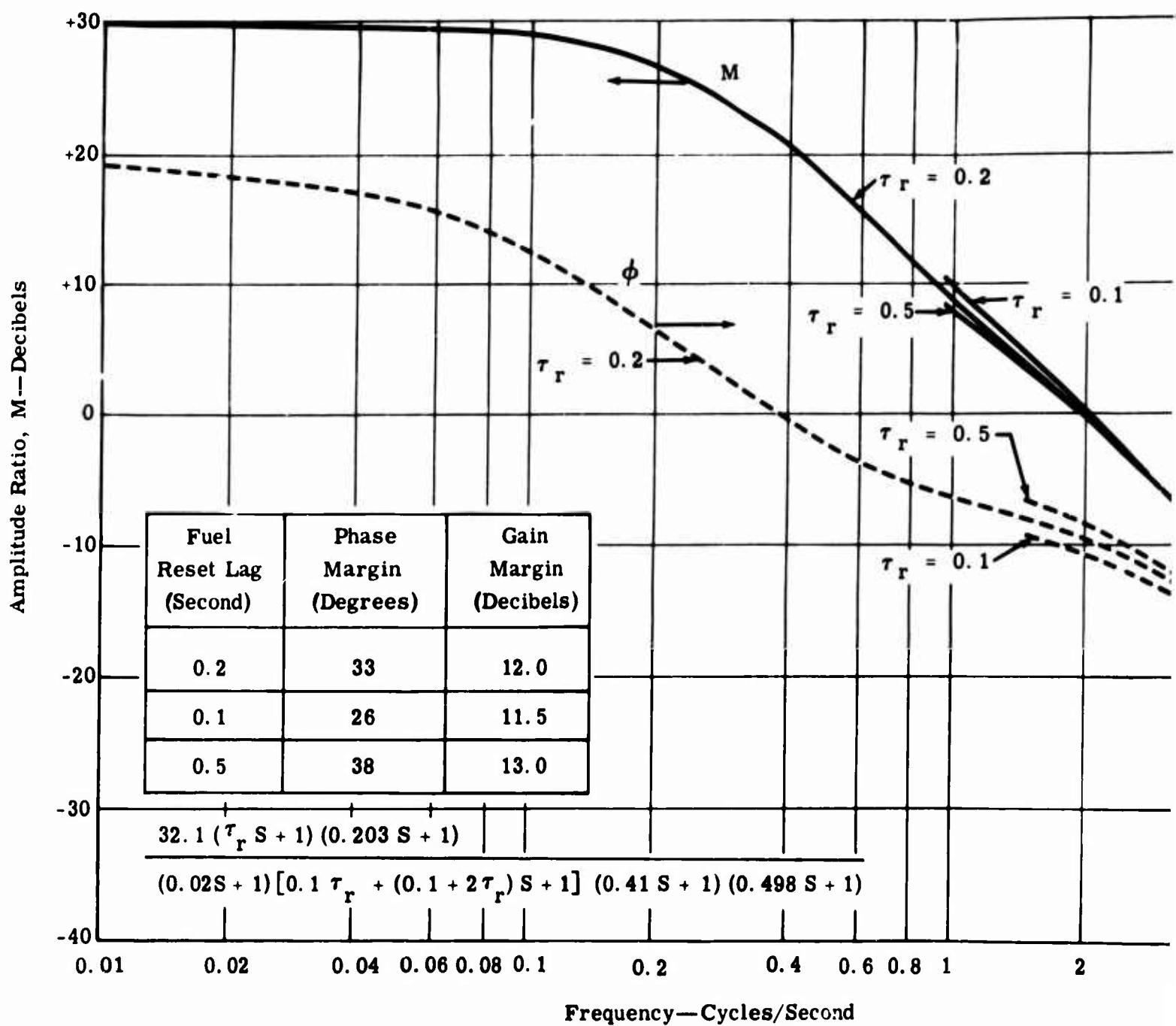
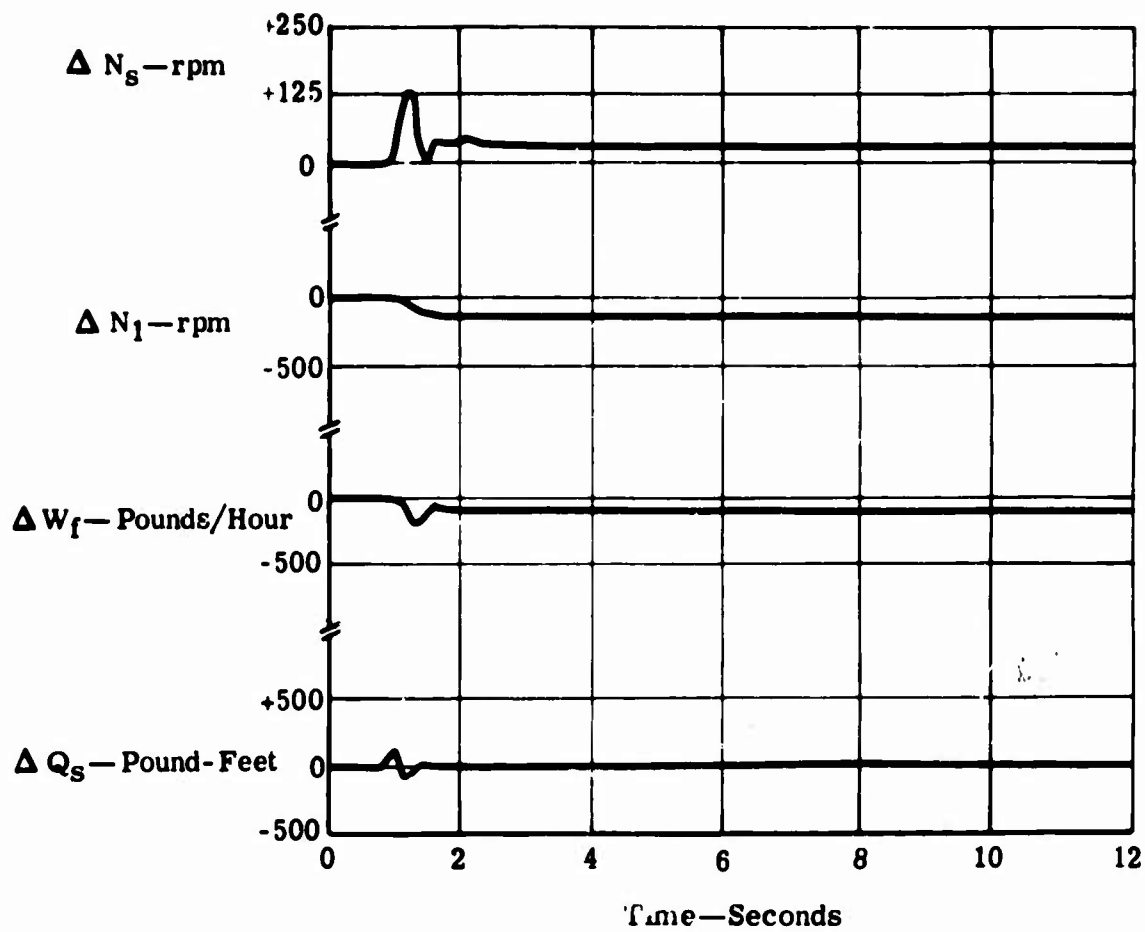
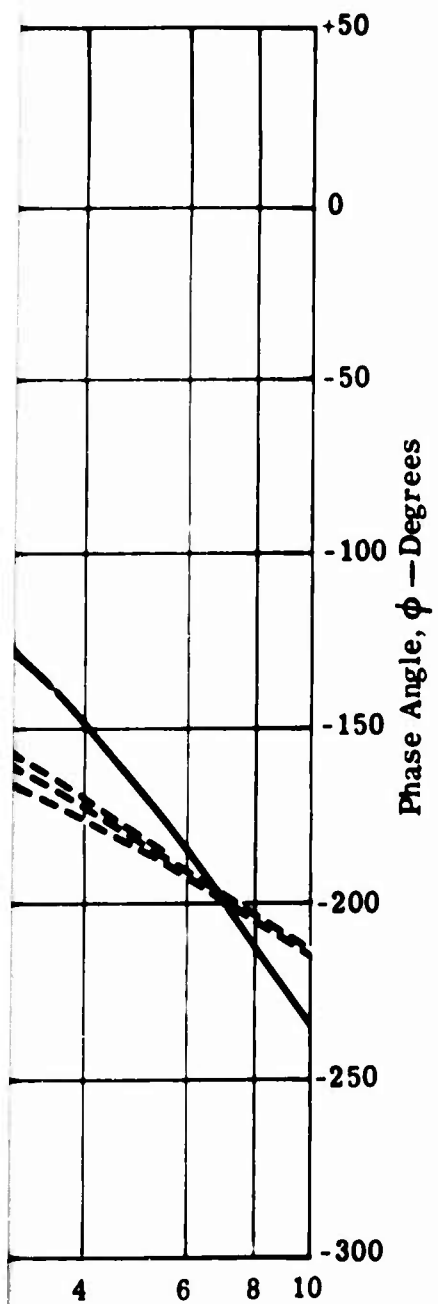


Figure 11. Fuel Flow Governor With Lagged Gain Reset, Low Power-Decoupled Rotor—5-Percent Droop Governor.

A



B

TABLE IV		
STABILITY MARGINS FOR A 10-PERCENT GOVERNOR WITH A GOVERNOR LAG OF 0.5 SECOND		
Flight Condition	Low Frequency Phase Margin (Degrees)	Torsional Gain Margin (Decibels)
High Power	59	7.5
Low Power	28	7.0
Decoupled Rotor	7	2.4

Direct Fuel Flow/Compressor Discharge Pressure Governor

The basic block diagram defining this mode of control is shown in Figure 13. K_p equals the governor proportional gain in pounds per hour per rpm.

This mode of control is a proportional power turbine governor in which the parameter W_f/CDP is proportional to the engine speed error. The dynamic characteristics of the engine-control-rotor system with this mode of control are such that at high power with a 5-percent speed droop governor, the governor lag must be increased to 0.5 second to result in a torsionally stable system. As in the direct fuel flow governor mode, this amount of governor lag results in decoupled rotor instability (gain margin equals 1.3 decibels). A 10-percent droop governor with a governor lag of 0.5 second results in the stability margins presented in Table V.

TABLE V		
STABILITY MARGINS FOR A 10-PERCENT DROOP GOVERNOR WITH A GOVERNOR LAG OF 0.5 SECOND		
Flight Condition	Low-Frequency Phase Margin (Degrees)	Torsional Gain Margin (Decibels)
High Power	22	6.5
Low Power	28	14.3
Decoupled Rotor	11	4.7

This reduced governor gain provides only 11 degrees phase margin at low power decoupled rotor conditions. The governor droop would have to be increased to at least 15 percent to provide sufficient phase margin for decoupled rotor operation.

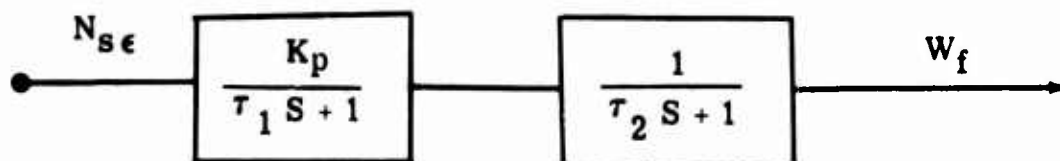


Figure 12. Direct Fuel Flow Governor Block Diagram.

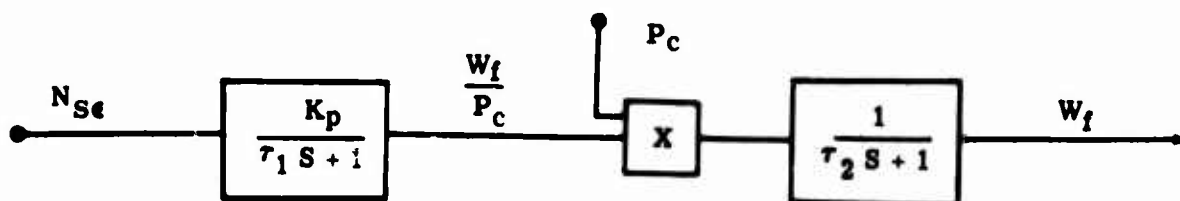


Figure 13. Direct Fuel Flow/Compressor Discharge Pressure Governor Block Diagram.

Gas Producer Fuel Flow Governor Reset Mode

The basic block diagram defining this mode of control is shown in Figure 14, where:

- K_g = Gas producer governor gain, pounds per hour per r. p. m.
- K_e = Gas producer governor reset gain, r. p. m. per r. p. m.
- N_1 = Gas producer speed, r. p. m.
- τ_3 = Gas producer speed sensing control lag
- τ_e = Engine gas producer time constant

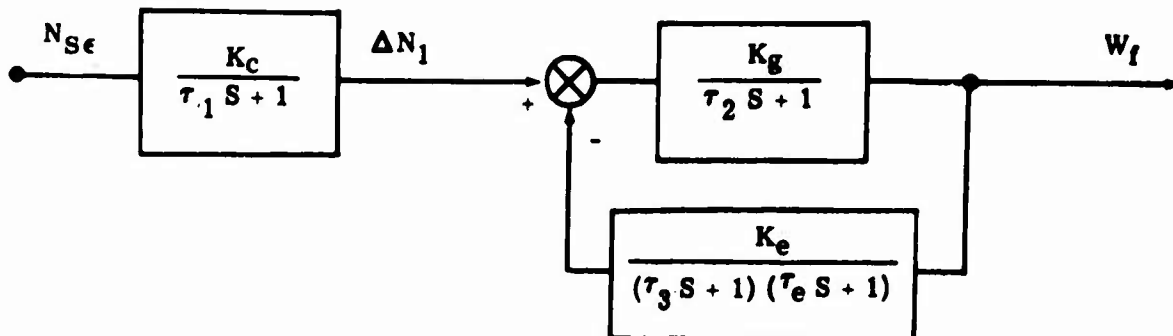


Figure 14. Gas Producer Fuel Flow Governor Reset Mode Block Diagram.

In this mode, the power turbine governor resets the gas producer governor as a function of shaft speed error. The dynamic characteristics of this engine-control-rotor system require a governor lag (τ_1) of about 2.0 seconds to provide a torsionally acceptable system at high power conditions. The stability margins listed in Table VI are based on a 10-percent speed droop governing system with the gas producer governor gain set at 2.0 pounds per hour per rpm.

TABLE VI		
STABILITY MARGINS BASED ON A 10-PERCENT SPEED DROOP GOVERNING SYSTEM WITH THE GAS PRODUCER GOVERNOR GAIN SET AT 2.0 POUNDS PER HOUR PER RPM.		
Flight Condition	Low Frequency Phase Margin (Degrees)	Torsional Gain Margin (Decibels)
High Power	68	8.5
Low Power	43	7.0
Decoupled Rotor	54	11.0

Gas Producer Fuel Flow/Compressor Discharge Pressure Governor Reset Mode

The basic block diagram defining this mode of control is shown in Figure 15. This mode is very similar to the gas producer fuel flow governor reset mode, except that W_f/P_c rather than W_f is the controlled parameter.

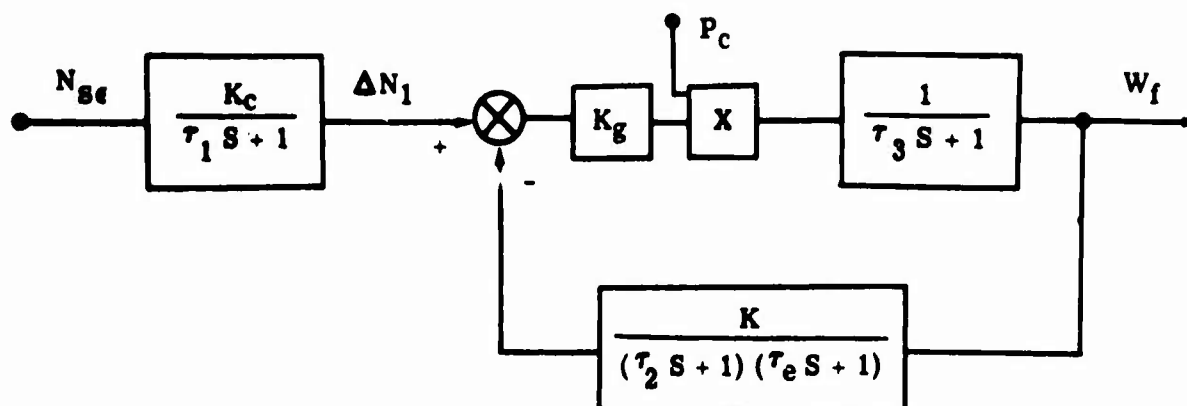


Figure 15. Gas Producer Fuel Flow/Compressor Discharge Pressure Governor Reset Mode Block Diagram.

The gas producer governor gain, therefore, is expressed in pounds per hour per inch of mercury per rpm. Based on a 10-percent speed droop governing system, a governor lag (τ_1) of 2. seconds, and a gas producer governor gain of 0.00685 pound per hour per inch of mercury per rpm, the stability margins were determined as shown in Table VII.

TABLE VII		
STABILITY MARGINS BASED ON A 10-PERCENT SPEED DROOP GOVERNING SYSTEM, A GOVERNOR LAG OF 2 SEC, AND A GAS PRODUCER GOVERNOR GAIN OF 0.00685 POUND PER HOUR PER INCH OF MERCURY PER RPM		
Flight Condition	Low Frequency Phase Margin (Degrees)	Torsional Gain Margin (Decibels)
High Power	66	6.0
Low Power	38	14.0
Decoupled Rotor	37	10.8

Direct Fuel Flow/Compressor Discharge Pressure Governor With Integral Reset

The basic block diagram defining this mode of control is shown in Figure 16. This mode is similar to the direct fuel flow/CDP governor (see Figure 33) except that a proportional-plus-integral control is utilized. The

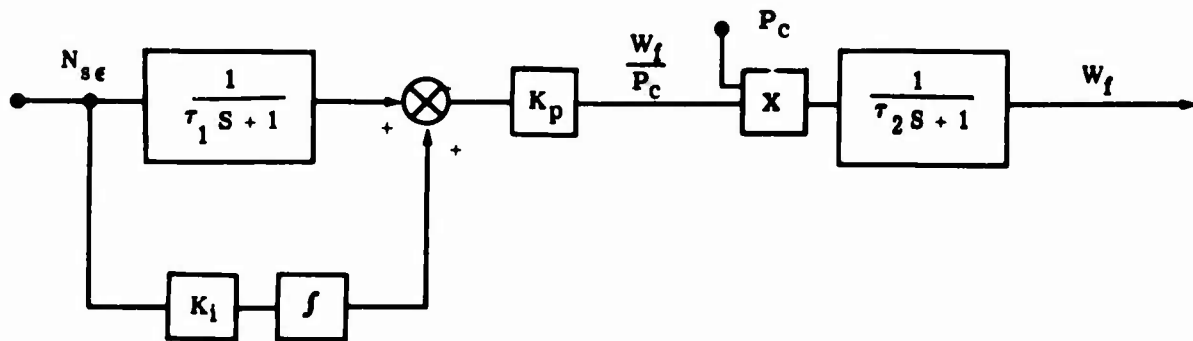


Figure 16. Direct Fuel Flow/Compressor Discharge Pressure With Integral Reset Block Diagram.

addition of the integral reset tends to reduce the torsional and low frequency phase margins. A Bode analysis at high power indicates that for a 10-percent droop governor with a 0.5-second lag, increasing the integral reset gain from 0 to 1.5 rpm per second per rpm reduces the low frequency phase margin from 22 degrees to zero. Therefore, to maintain a sufficient stability margin with this mode, the proportional gain would have to be reduced by 50 percent and the integral gain would have to be limited to about 0.1 to 0.2 rpm per second per rpm. The stability margins in Table VIII are based on a 15-percent droop proportional gain, a governor lag of 0.5 second, and an integral gain of 0.1 rpm per second per rpm.

TABLE VIII		
STABILITY MARGINS BASED ON A 15-PERCENT DROOP PROPORTIONAL GAIN, A GOVERNOR LAG OF 0.5 SECOND, AND AN INTEGRAL GAIN OF 0.1 RPM PER SECOND PER RPM.		
Flight Condition	Low Frequency Phase Margin (Degrees)	Torsional Gain Margin (Decibels)
High Power	27	10.5
Low Power	33	20.0
Decoupled Rotor	20	8.5

This mode of control would undoubtedly be undesirable due to extreme speed overshoots during gross transients and slow and sluggish response (system frequency equals 0.2 to 0.3 cycle per second).

TRANSIENT RESPONSE ANALYSIS

The transient response analysis indicated that all proportional governing modes are equivalent in their response on increase collective load transients. This is true, provided that collective-power turbine lever coordination is employed. The transient rotor speed droops were in the range of 8.0 to 8.5 percent for a 1-second full range load transient.

Certain modes require a lower governor gain for stabilization. In a collective-coordinated system, the power turbine governor gain has little effect on the transient rotor speed. In this configuration, the power turbine lever reset provides a lead signal to the control system to initiate the power change prior to power turbine speed change. If the governor gain is reduced 50 percent, the coordination gain must be increased by the same amount to trim out the steady-state droop. The result is that essentially the same magnitude of lead is provided regardless of the governor gain.

Lag functions for torsional stability will not significantly affect the transient response to load changes if they are not introduced in the control loop between collective lever and fuel flow. This can be accomplished by imposing the dynamic function in the speed sensing loop with certain modes, or in a feedback loop on others.

The response to a rapid collective lever decrease was good for all proportional governing modes, limiting the transient overspeed to less than 4 percent. However, they are not exactly the same, with the compressor-discharge-pressure-compensated and the lagged-gain-reset modes being slightly slower. With these modes, the collective lever coordination effect can not, alone, reduce the fuel flow to the low deceleration fuel limit schedule. Instead, the fuel reduction is dependent upon the power turbine overspeed, compressor discharge pressure, and/or elapsed time. The result is a somewhat slower deceleration rate than the engine is capable of, when using any of these modes.

The most rapid-responding mode on a collective lever decrease is gas producer fuel flow governor reset, limiting the transient overspeed to only 2 percent. All other modes ranged between 2 and 4 percent in transient overspeed on a 1-second full range load reduction.

The transient response of the direct fuel flow/compressor discharge pressure governor with integral reset (isochronous) is not acceptable, resulting in excessive transient speed excursions and stabilization times. This is because of the gains and dynamics required for stability and the

absence of the load change lead signal due to the elimination of the collective lever coordination. The transient underspeed was 16 percent on a 1-second collective load increase, and the overspeed was 12 percent on a rapid load decrease. Also, the stabilization time was excessive, with several overspeeds and undershoots.

GOVERNING ACCURACY ANALYSIS

Coordination of the helicopter collective lever and the power turbine governor lever would be employed to trim out the speed variation with load associated with proportional governors. Transient response studies have indicated that with the employment of coordination, the magnitude of the power turbine governor gain (or droop) does not affect the transient rotor speed droop (or overspeed) on collective lever load transients. However, the torsional and low frequency governing stability is improved by using a low gain governor.

A cursory analysis was conducted to determine the effect of other helicopter operating conditions, wherein the load varies at a fixed collective, upon the governing accuracy.

Table IX summarizes the steady-state rotor speed variations that could occur at a constant collective lever position and governor setting.

TABLE IX		
STEADY-STATE ROTOR SPEED SHIFT AT CONSTANT COLLECTIVE LEVER		
	5-Percent Droop Governor (Percent)	10-Percent Droop Governor (Percent)
Ambient Temperature (59°F to -65°F)	-0.8	-1.7
Altitude, With a Pressure Compensated Governor	0	0
Altitude, Without Pressure Compensation (Sea Level to 10,000 ft)	1.5	2.7
Rate of Climb (Hover to 40 fps)	1.2	2.2
Horizontal Velocity (Hover to 50 mph)	1.8	3.3
Tail Rotor Demand (0 to 10 percent)	0.8	1.4

These data indicate that the 10-percent droop governor design would result in almost twice as much variation in rotor speed in operation as the 5-percent droop design. The governor mode should be one that will allow utilization of a steady-state gain equivalent to 5 percent or less.

EVALUATION OF GAS PRODUCER CONTROL REQUIREMENTS

The basic operating requirements and limits of the engine and helicopter have been defined for the multiengine helicopter. The engine requirements and limitations are based on Allison's engine specifications (oriented to the military specifications), design practice, and experience. The helicopter requirements and limits are based on the results of engineering meetings with helicopter manufacturers—i.e., Boeing Vertol, Sikorsky Aircraft, and Lockheed Aircraft.

The evaluation of these requirements resulted in the selection of the gas producer functional design illustrated in Figure 17. Some of the significant features of this design are as follows:

- Gas producer control of the hydromechanical type
- Compatibility with either electrical or mechanical signal transmission from helicopter to engine controls
- Automatic sequencing and control of engine fuel flow during starting
- Emergency power operation capability, with both manual and automatic selection—manual by condition lever (or a selection switch) and automatic by a malfunction detection system
- Closed-loop turbine temperature limiting for steady state, with settings for intermediate and emergency (open-loop limiting will be provided on starts and power transients.)
- Torque limiting function relegated to the pilot, monitoring the indicators and limiting load application
- Gas producer speed governing for locked-rotor operation, with the condition lever at ground idle
- Power turbine governor that utilizes the gas producer control metering valve to accomplish the fuel and power control
- External control adjustments on the gas producer governor intermediate and ground idle speed settings

Included herein are explanations of the considerations and factors that led to the selection of this design.

The gas producer control illustrated in Figure 17 employs compressor discharge pressure as the pressure compensating parameter. This functional design could also employ compressor inlet pressure compensation.

CONTROL SIGNAL TRANSMISSION

Two different methods of cockpit signal transmission to the gas producer and power turbine controls are presently employed, i.e., electrical and

mechanical. Mechanical transmission has been considered more reliable than the electrical because pilots can "muscle" the levers around to overcome sticking or friction and it is more resistant to destruction by local fires. However, there are production helicopters presently in operation that utilize fly-by-wire, and have demonstrated satisfactory reliability with this concept.

The heavy lift helicopter design, which will be a multiengine configuration, may result in a pilot location fairly removed from the engines. This, coupled with the use of more than two engines, may make the electrical transmission system a desirable approach for this aircraft. An evaluation by the helicopter companies will have to decide between design complexity and reliability.

Signal transmission can be a significant factor in the control system design since it may influence the interface design and the mechanization of certain functions. The present indications are that the transmission method employed may be either mechanical or electrical and that the control design must be compatible with either. This is true for the condition lever signals to the gas producer controls and the collective lever trim or speed setting trim signal to the power turbine governors.

STARTING OPERATION AND CONTROL

Each engine will be started separately, utilizing individual condition levers and start switches for each. The engines will not be started simultaneously because of the associated large starter power that would be required to motor all engines.

Automatic sequencing and control of the engine fuel flow during starting is required to prevent the occurrence of explosive light-off, excessive turbine temperatures, and/or compressor surge. This concept minimizes the responsibility of the pilot with regard to critical sequencing or manipulation of engine control levers or switches during starting. The start procedure may consist of positioning an engine condition lever at START-GROUND IDLE and then actuating an engine start switch.

To provide automatic sequencing of the fuel flow initiation during starting, the fuel cutoff valve opening point must be delayed until the gas producer speed exceeds the engine light-off speed. This can be accomplished by utilizing the gas producer signal generated in the control to operate the fuel cutoff valve. The start fuel flow would be scheduled to allow successful completion of the gas producer acceleration to ground idle and would

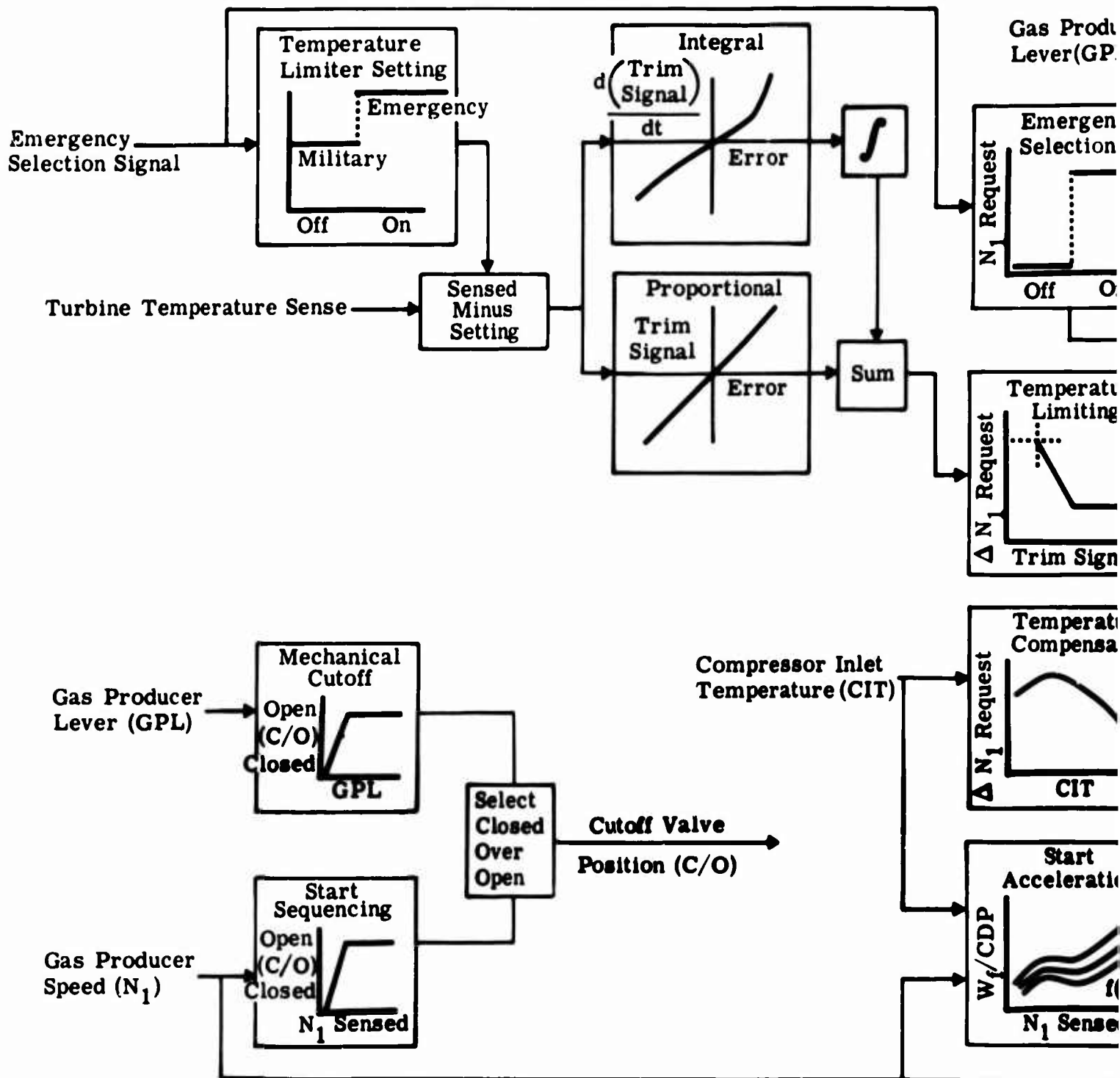
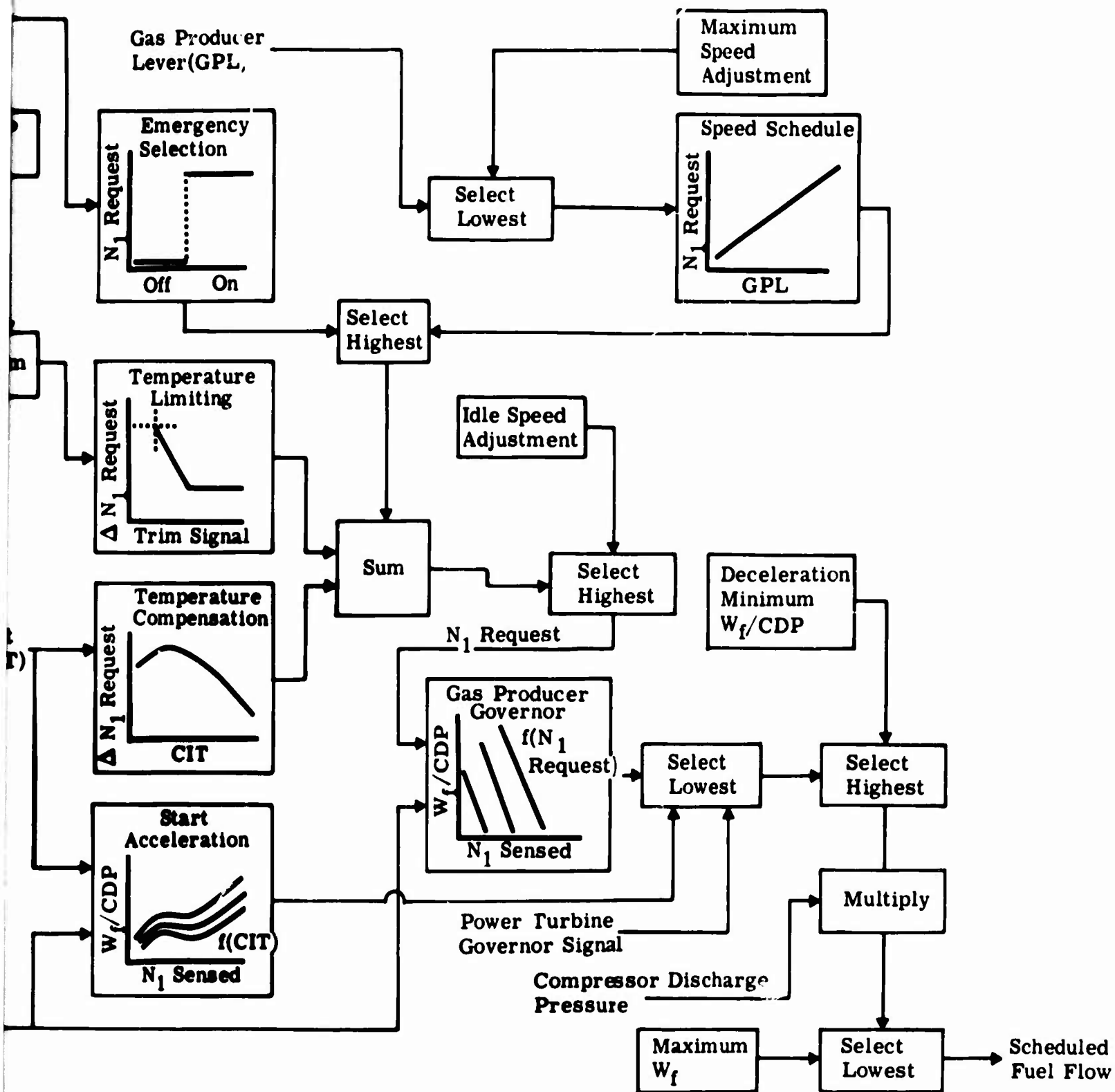


Figure 17. Gas Producer Control System Functional Diagram.

A



B

be free from excessive turbine temperatures and compressor surge. The start fuel would be scheduled to vary with the gas producer speed, with air temperature and pressure compensation.

EMERGENCY OPERATION AND CONTROL

Future helicopter engines for the multiengine helicopter will be required to provide a power level capability greater than the military (or intermediate) rating. This would be a power 15 to 20 percent higher than the military rating, with a time duration limit of approximately 30 seconds. To provide this, combustion gas temperatures 150° to 200°F higher than military will be required. Because of the associated high combustion gas temperatures (and gas producer speed), operation at this condition may require hot section inspection, engine removal, and/or overhaul.

Requirements for Emergency Power

Two operational conditions could occur with the helicopter which would require emergency power operation—i.e., extra-heavy load lifting and engine power malfunction.

The extra-heavy load lifting operation is one where the pilot determines that sufficient engine power may not be available to enable successful take-off or flight. This may be due either to the necessity for lifting a heavier-than-design load, to extreme ambient conditions, or to depreciated engines. For this condition, the pilot could be required to determine the need and then to manually select emergency operation capability. The lift-off operation would be of a gradual nature, allowing sufficient time for the pilot to initiate the selective action.

The engine power malfunctions of prime concern are engine flameouts, failure of coupling mechanism between engine(s) and rotor system, and control malfunctions causing loss of power availability. If any of these malfunctions occur while the helicopter is in a critical flight mode, emergency power capability on the operating systems must be provided to allow time for recovery from the critical mode. For these cases, an automatic detection and emergency operation capability selection system may be required, since the lag associated with pilot detection and reaction may be too long to assure safe recovery.

Initiation of Emergency Power Capability

During all normal engine operation, the control system limits the turbine temperature and gas producer speed in accordance with the military (or

intermediate) limits of the engine. These control functions are required to prevent inadvertent operation above these limits during the normal steady-state and transient conditions. This is necessary since operation at emergency power may require engine inspection and/or overhaul. The limiter settings, therefore, will not allow operation at emergency power. To enable emergency power operation, the limiter must be reset to the limits associated with emergency power.

As indicated in the requirements for emergency power, the two operational conditions which require emergency power capability require different methods of initiation. For the extra-heavy load pickup, the pilot could be required to select emergency capability. For the engine power malfunction case, a signal generated by a malfunction detector will be provided to select emergency capability automatically. The manual selection could be effected through positioning of the cockpit engine condition lever(s). Besides the usual OFF, START-GROUND IDLE, and FLY positions, an EMERGENCY position could be provided. (Separate levers would be utilized in the cockpit for independent condition control of each engine.) Also, a means would be required to utilize the malfunction detector signal (probably electrical) in the gas producer control to accomplish the automatic reset.

Another approach would be to provide a single means for resetting the gas producer control for emergency, whether the demand was initiated by the pilot or the malfunction detector. A single cockpit switch would be required, capable of operating all engines simultaneously. This switch would have three positions, i. e., EMERGENCY, OFF, and AUTOMATIC. When in the EMERGENCY position, all gas producer controls would be reset to provide emergency capability. When in the AUTOMATIC position, a malfunction detector component would be coupled into the system with the capability of automatically selecting emergency. The OFF position would disarm the malfunction detector. Figure 18 is a schematic of the portion of a gas producer control associated with establishing the maximum gas producer governor speed setting, illustrating the reset mechanism for emergency capability.

Detection of Emergency Power Operation

In the helicopter application, the selection of emergency power capability, either manually or automatically, does not mean absolutely that emergency will be (or has been) used. The selection of emergency capability would merely lift the military power control limiters to make emergency power available. The engines would not be operated at emergency power

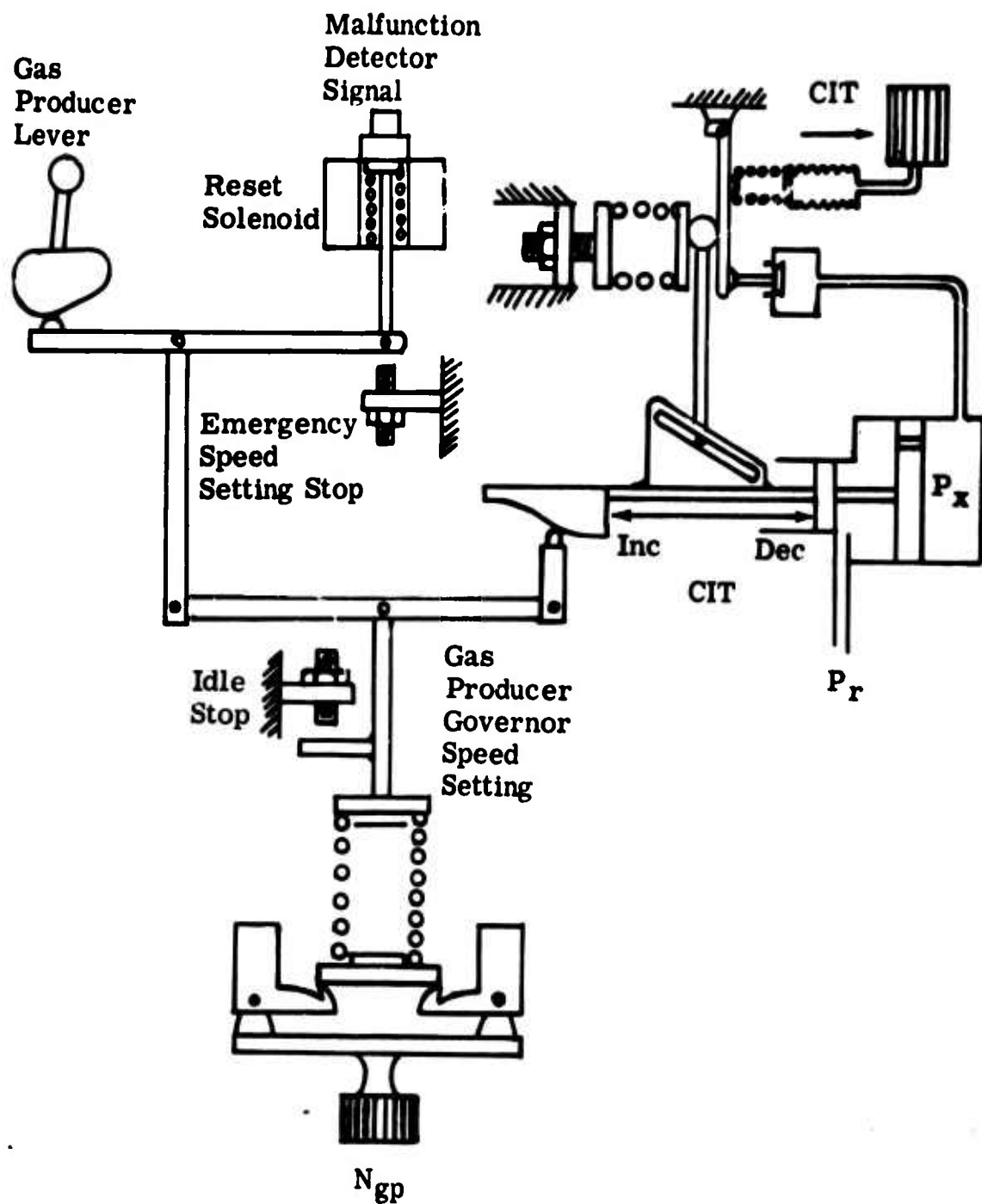


Figure 18. Schematic of Gas Producer Control Mechanization With Malfunction Detector Reset.

unless the helicopter rotor loading (power demand) becomes great enough to require a power level greater than military from the operating engines. The power turbine governors would detect this need and increase the engine(s) power accordingly.

To prevent unnecessary field servicing and premature engine removal, some method of indicating the type of operation to which the engine has been subjected may be desired. This system would, by direct reading, indicate whether the engine(s) had actually been operated at emergency power. The system might be as extensive as a time-temperature totalizer, which utilizes a turbine temperature sensor and clock to indicate accumulated time durations in different temperature ranges. However, the system might be as simple as an indicator "flag" or a "fuse" that is dispatched when the turbine temperature exceeds a specific level.

TURBINE TEMPERATURE LIMITING

The reason for concern about the steady-state turbine temperature is that engine life is greatly shortened by very high turbine temperature operation. To achieve the specified engine life, engine operation must be retained within the turbine temperature limits defined by the model specification. This includes steady-state, power-transient, and starting operation. Control studies have resulted in the conclusion that closed-loop turbine temperature limiting is required for steady-state operation, but open-loop limiting would be satisfactory for transient and start protection.

Steady State

The two significant turbine temperature operating limits for the helicopter gas turbine engines are INTERMEDIATE (or MILITARY) and EMERGENCY. Operation at military is generally limited to a continuous time period of 30 minutes, while emergency may be limited to 30 seconds. Normal (maximum continuous) is another temperature level that is normally specified for gas turbine engines, but the mission profile of the helicopter generally does not require consideration of this limit. Instead, the 30-minute military turbine temperature level, along with emergency, are the limits of significance.

The steady-state turbine temperature limiting could be accomplished either by the pilot monitoring the temperature indicator(s) and manually correcting, or by automatic control. In the multiengine helicopter, the pilot must

not be required to perform the limiting function associated with the limits that are short-time restricted. This is especially true because of the multiple engines and indicators involved.

Two types of automatic limiting approaches were considered; i. e., open loop, according to a predetermined schedule, and closed-loop, utilizing the turbine temperature sensor signal for control. The open-loop approach consists of scheduling the gas producer control as a function of certain parameters (not including turbine temperature) to limit the temperature. The closed-loop turbine temperature limiting approach would utilize the thermocouple developed signal in an electronic amplifier-control to develop an electrical error signal. This signal would then be utilized by the gas producer control to effect a fuel flow change and to limit the turbine temperature.

A single maximum gas producer governor speed setting would not provide satisfactory temperature limiting. The turbine temperature-gas producer speed relationship of the engine is affected by the compressor air temperature, accessory or aircraft air bleed, and engine variations in production and field service. There would also be production and field service variations in the open-loop control scheduling of the governor setting.

The steady-state turbine temperature limiting selected is a combination open-loop/closed-loop design. The maximum gas producer governor setting is varied as a function of compressor air temperature, with compressor discharge pressure compensation of the governor's effect on the metered fuel flow. A turbine temperature error signal generated by an electronic amplifier limiter is utilized to trim the governor to correct for the inaccuracy that results from open-loop scheduling. The open-loop compensation is required to prevent extreme overtemperature operation in power transients where the inherent lag of a conventional turbine temperature sensing system (thermocouples) is significant and to minimize the authority that must be allocated to the electronic control (malfunction consideration).

The closed-loop limiter signal would be capable only of reducing the governor setting established by the hydromechanical control, so that malfunctions in the sensing and control loop cannot cause extreme overtemperatures. A proportional-plus-integral limiter design is required to provide stability and accurate temperature limiting. A linearized analog computer

study of this operation indicated that a proportional gain (ΔN_1 governor setting/ Δ temperature error) of 0.015 percent/ $^{\circ}\text{F}$ and an integrator gain (ΔN_1 governor setting/ Δ time/ Δ temperature error) of 0.009 percent/second/ $^{\circ}\text{F}$ are required to obtain proper control with this design. This is based on using a gas producer governor gain ($\Delta W_f/\text{CDP}/\Delta N_1$) of 20 percent/percent.

The amplifier-limiter temperature reference setting would be normally set for the military limit. When emergency capability is selected, the temperature reference must be reindexed to the appropriate level, utilizing the command signal that is employed by the gas producer control for emergency selection to effect the change.

The functional diagram of the gas producer control system (Figure 17) illustrates the temperature limiting control functions.

Starting

The engine limit during starting is normally turbine temperature. With the type of fuel control which would be utilized on engines for multiengine helicopters, the starting fuel flow will be scheduled as a function of the gas producer speed, compressor air temperature, and pressure. This open-loop control regulates the starting fuel flow in accordance with a pre-determined schedule to provide operation within the start temperature limit.

Because of the production and field service variations of engines, controls, and fuels, the fuel schedule can not provide a precise turbine temperature. This is especially true when considering initial starts (cold) and restarts (hot), which characteristically are different in their requirements.

Two approaches were considered for preventing overtemperature operation during starting. First, select a start schedule that, with all variations considered, will produce turbine temperatures no greater than the start limit. Second, select a start schedule that might in certain instances be too rich, and utilize a closed-loop turbine temperature limiter to trim this schedule.

The second approach is ideal from the standpoint of providing the maximum engine assist during the starting process. This approach is utilized on engine-control designs where additional control mechanisms are not required to provide the function. This approach may also be warranted (or required) in applications which are marginal on stored energy for starting. However, the functional requirements for the start limiter are not

compatible with the desired functional design for steady-state limiting; therefore, special mechanisms would be required to provide the start limiting. The multiengine helicopter will probably utilize engines of a power class that cannot be started by stored energy, especially when considering multiple start attempt capability. The aircraft will probably utilize a small auxiliary power unit (APU) to generate the starting power required by the main engines. It is anticipated that the APU will be of a sufficient power class that operation of the engine precisely at the start turbine limit will not be required for satisfactory starting.

It is concluded, therefore, that a closed-loop start turbine temperature limiter will not be required for the engines in this application. The start fuel flow will be metered according to an open-loop predetermined fuel schedule. Since the present concept is that the engines will not be started simultaneously, pilot monitoring of the turbine temperature indicator of an engine during starting can be expected. In the event of an extreme condition (rich control, sick engine, etc), the pilot would be required to take appropriate corrective action, i. e., aborting the start attempt by actuating a fuel cutoff to that engine.

As was indicated, the present engine starting concept for the multiengine helicopter is that the pilot would initiate startup of an engine, awaiting completion of the startup of one engine before initiating startup of another. Simultaneous startup of multiple engines is generally considered to be impractical because the ambient of bleed required is more than the first engine can supply. If auxiliary power units (APU's) are considered for simultaneous startup of multiple engines, the size of the APU and associated equipment is so large as to be prohibitive.

Power Transients

The limits on acceleration transients are compressor surge and turbine temperature. Similar to the start schedule, the acceleration fuel flow can be scheduled as a function of gas producer speed, compressor air temperature, and pressure. The production and field service variations of engines, controls, and fuel will result in variations in the transient turbine temperatures with the open-loop scheduling.

As indicated, the accelerations are not solely limited to a constant level of turbine temperature over the gas producer speed range from idle to maximum, or to varying compressor air temperatures. The peak transient turbine temperatures are generally encountered only at the high gas producer speeds, above 90 or 95 percent. The effective range of operation of a single-temperature-level closed-loop limiter, therefore, would be small.

The gas producer accelerations of modern helicopter engines are generally too rapid to benefit from a closed-loop turbine temperature limiter. The response of the temperature sensors (generally thermocouples) will not be fast enough to detect and indicate the overtemperature condition during the rapid gas producer transient. Fast sensors could be employed for the transient protection, but the current devices would have short life at the temperature levels and in the environment of the turbine gases.

The control system would be complicated by the addition of the closed-loop temperature limiting on transients. Control studies have indicated that the temperature limiting function for transient protection must be accomplished in a manner different from that for steady state. Based on present-day technology, the turbine temperature limiter signal would be generated by an electronic amplifier control. The limiting function, if employed, could be introduced only as a trim on the hydromechanical acceleration schedule, with the trim authority (range) mechanically limited. This approach is required to retain the basic proven reliability of the hydromechanical control.

Previous experience has indicated that satisfactory transient fuel control can be achieved by the open-loop fuel scheduling. This experience, coupled with the unavailability of suitable temperature sensors, the limited range of effectivity, and the associated control complexity has led to the conclusion that closed-loop transient turbine temperature limiting is not desired.

TORQUE LIMITING

The torque limits of significance in the multiengine helicopter are associated with the helicopter transmission system. The engines will generally operate at turbine speeds that can be accepted directly by the helicopter transmission system. The engine manufacturer, therefore, will not provide a speed reducing gearbox. The high torque components are a part of the helicopter transmission system. Consequently, the torque limited components of the engine can tolerate a higher operating power level than those of the helicopter.

The helicopter system will have a net torque limit and a torque limit for each engine input. The system will generally permit operation at the net torque limit with a load sharing unbalance of 10 percent without exceeding the individual torque limits. Unbalance in engine torques is of no structural consequence as long as the net and individual limits are not exceeded.

The present philosophy on torque limiting for the helicopter is to restrict the collective (and cyclic) loading, with this responsibility allocated to the pilot. This approach is desirable because momentarily exceeding the helicopter limit(s) is not a stress rupture problem and momentary over-torque operation may be necessary in extreme maneuvers or emergencies. It is not desirable to accomplish the helicopter torque protection by limiting the available power through affecting the engine fuel flow.

Conventionally, the helicopter employs torque indicators for each engine, with two "red line" limits designated. One is for normal flight operation, while the other is for emergency operation. On two-engine aircraft, this is normally a single indicator with two needles. For a three- or four-engine system, the approach may be to provide a transmission net torque sensor and indicator, with appropriate "red line" limits. This would simplify the role of the pilot with regard to monitoring and limiting the system torque.

Steady State

The gas turbine engine characteristically will produce 40 to 50 percent more power at -65°F than at a standard ambient temperature, when operating at a constant turbine temperature (or gas producer speed) and power turbine speed. An engine which does not employ a speed reducing gearbox is normally designed to be safe from stress rupture at this high torque level. However, these high torque levels can be prevented from occurring by simply limiting the maximum metered fuel flow to the engine(s). The accuracy of this overtorque limiting will be on the order of 8 or 10 percent at 100 percent power turbine speed. Limiting of overtorque operation at cold ambients must be based on the emergency power rating. The single-level maximum fuel flow stop would be set for this power condition and would be practically ineffective with regard to providing limiting during normal flight operation.

Transients

In very rapid load applications, transient torques 10 to 20 percent higher than the steady-state limit could be experienced. This is due to the transient rotor speed droop characteristic associated with the free turbine engine when making very rapid load applications (1 second from autorotation to intermediate power), and the overfueling that occurs during the gas producer transient. It is not anticipated that this overtorque level or duration will be of sufficient importance to require the employment of special engine control devices. First, the helicopter transmission system will be

designed to accept the emergency torque rating without stress rupture occurring, and the transient torques during normal operation should not exceed this level. Second, the 1-second full range load application is extremely rapid for a multiengine helicopter and is not anticipated to be normally utilized.

LOCKED ROTOR OPERATION

Locked rotor operation may be required to allow checkout of an engine for maintaining the aircraft in standby readiness, or to prevent extended operation at low helicopter rotor speeds where blade flapping is potentially hazardous. The engine control during locked operation cannot be relegated to the power turbine governor because of the zero rotation condition. The gas producer control, therefore, must regulate the gas producer speed at the locked rotor condition.

The engine control during this operation will be maintained by the gas producer governor(s), providing control at a speed slightly higher than the minimum self-sustaining speed. This would provide the minimum torque level that can be achieved with the engine during locked-rotor operation. The START-GROUND IDLE condition lever position would be selected to achieve minimum torque on all engines. It would also be possible to operate with some of the engines not operating, with their condition levers in the OFF position. This would shut off the fuel flow to these engines.

GOVERNOR FUNCTIONAL INTEGRATION

Three basic methods of integrating the power turbine governor function into the fuel control system were evaluated. First, the power turbine governor and gas producer controls are both directly coupled into the fuel system in series, with the power turbine governor between the gas producer control and the fuel nozzle. The second method utilizes the gas producer control for all fuel metering, with a power turbine governor to develop a reset signal to effect the gas producer control operation. The third method involves the integration of both the gas producer control and the power turbine governor functions into the same component, with a power turbine speed sensor to provide the signal for the governor function. It has been concluded that functionally the reset (second method) or the integral control-governor (third method) is desirable, rather than the series governor. However, the differences are slight and specific features of a particular engine design or arrangement may negate these advantages.

The desirability of one method over another is not generally limited to functional considerations. It is, in the practical case, related to mechanical design considerations. For example, if an existing gas turbine engine and control system are being adapted for a helicopter application, the reset governing and integral component methods may not be desirable because they may require extensive gas producer control modifications. The series governing method could be implemented by merely adding a power turbine governor, without altering the gas producer control.

In some cases, the engine design may indicate that one method is more desirable than another. For example, in an aft-drive free turbine engine, the power turbine governor drive may be at the aft end of the engine. The series governing method may not be desirable because the total gas producer metered fuel flow would have to be transmitted past the hot section of the engine to the governor location and then back to the fuel nozzles. Fire shielding to protect fuel lines in the vicinity of the engine hot section would impose penalties of increased weight and cost and of decreased maintainability and safety.

Reset Governor

With this governing method, the power turbine governor-generated signal is employed in the gas producer control computer section to modify its scheduling. Figure 19 is a schematic diagram of a hydromechanical power turbine governor and gas producer control design, illustrating their functional integration. The integration of the power turbine governor signal in this manner is desirable because it can make effective use of the acceleration and deceleration fuel limit schedules during governing and because of the altitude pressure compensation of the gas producer control.

This method also provides design flexibility, allowing either a hydromechanical or an electronic power turbine governor to be employed with the hydromechanical gas producer control. This is the only method adaptable to the single-governor approach.

The disadvantage of this method is that the governor reset function must be provided in the gas producer control; however, it may prevent the utilization of existing designs. In a new design, this function could be specified initially and would not suffer this disadvantage. In existing designs, modifications to provide the reset capability may not be impossible.

Integral Control-Governor

The integral gas producer control-power turbine governor method is, from the functional standpoint, identical to the reset method. The major difference is that the function is more closely coupled into the gas producer control. As a result of the composite system, the integral control-governor should be smaller and lighter in weight. This method could readily be employed if instigated in the initial design of a new control. The required modifications would be fairly extensive for an existing control.

Figure 20 is a schematic illustrating the type of mechanization that would be required with this concept. A power turbine speed sensor component is required to generate a signal to be employed in the control-governor component.

Series Governing

With the series governing method, the gas producer control fuel flow output during all power turbine governing operation is established by the acceleration fuel limit schedule. The gas producer control output flow is received by the power turbine governor which then bypasses back to the fuel pump any fuel which is not required to support the load. The power turbine governor fuel scheduling is essentially independent of the gas producer speed and compressor discharge air pressure. A disadvantage of this method is that the deceleration fuel schedule provided by the gas producer control would not be functional during power turbine governing. Another disadvantage is that the power turbine governor would not be altitude compensated and would govern at higher power turbine speeds at altitude than at sea level. These disadvantages could be overcome but would require added complexity in the governor design to do so. The bypass valve of the governor must also be of a design that would provide zero leakage when closed to transmit the total acceleration schedule fuel flow to the engine in gross transients.

This concept should not be utilized when designing a new control system for the engines of a multiengine helicopter.

EXTERNAL CONTROL ADJUSTMENTS

In general, the control system is designed so that the engine operation will be automatically maintained within its operating limits throughout the guaranteed service life. Modifications of the control scheduling and settings which could upset this functioning should not be allowed. However, certain types of external control adjustments may be desirable to minimize the production and field service problems.

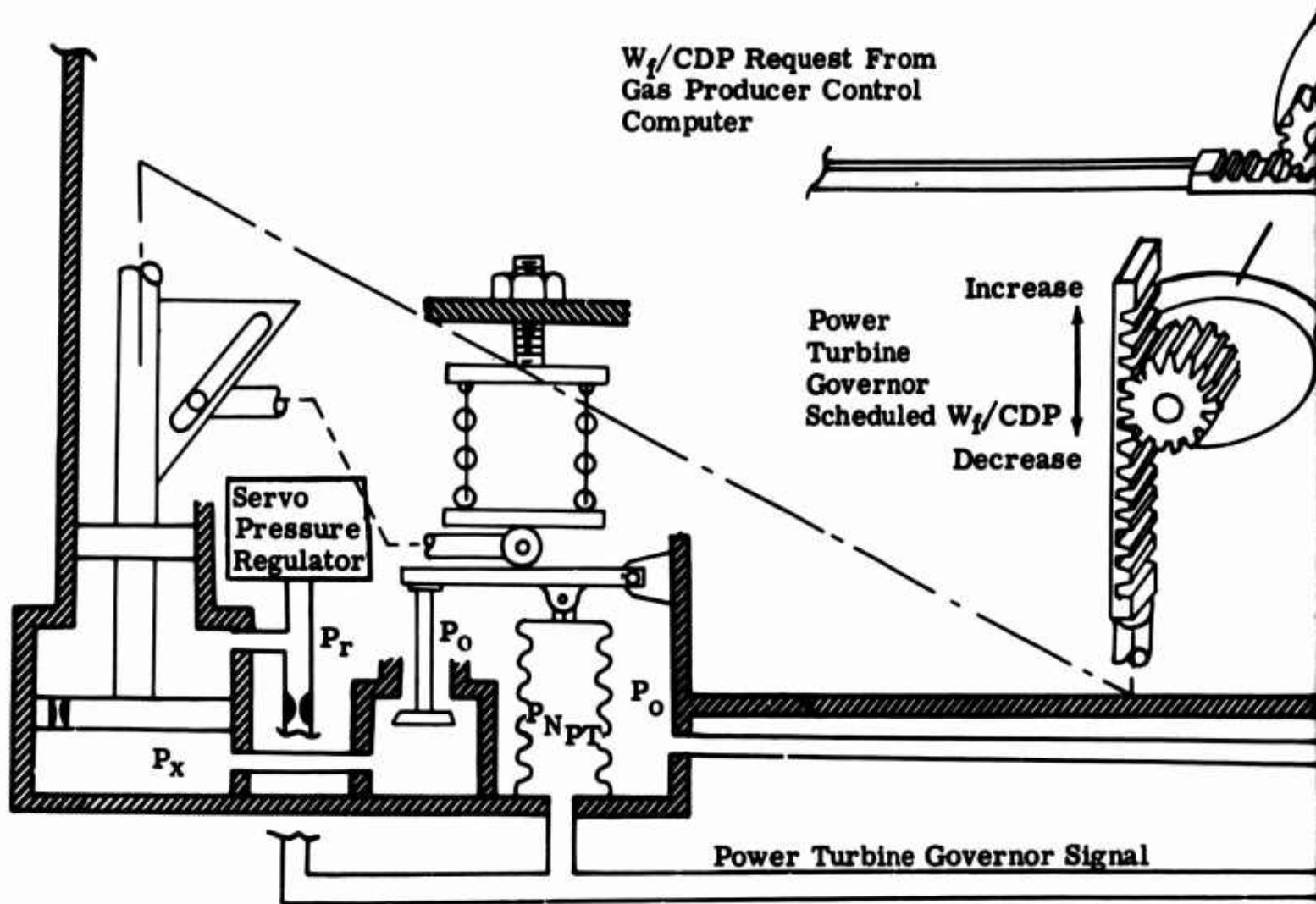
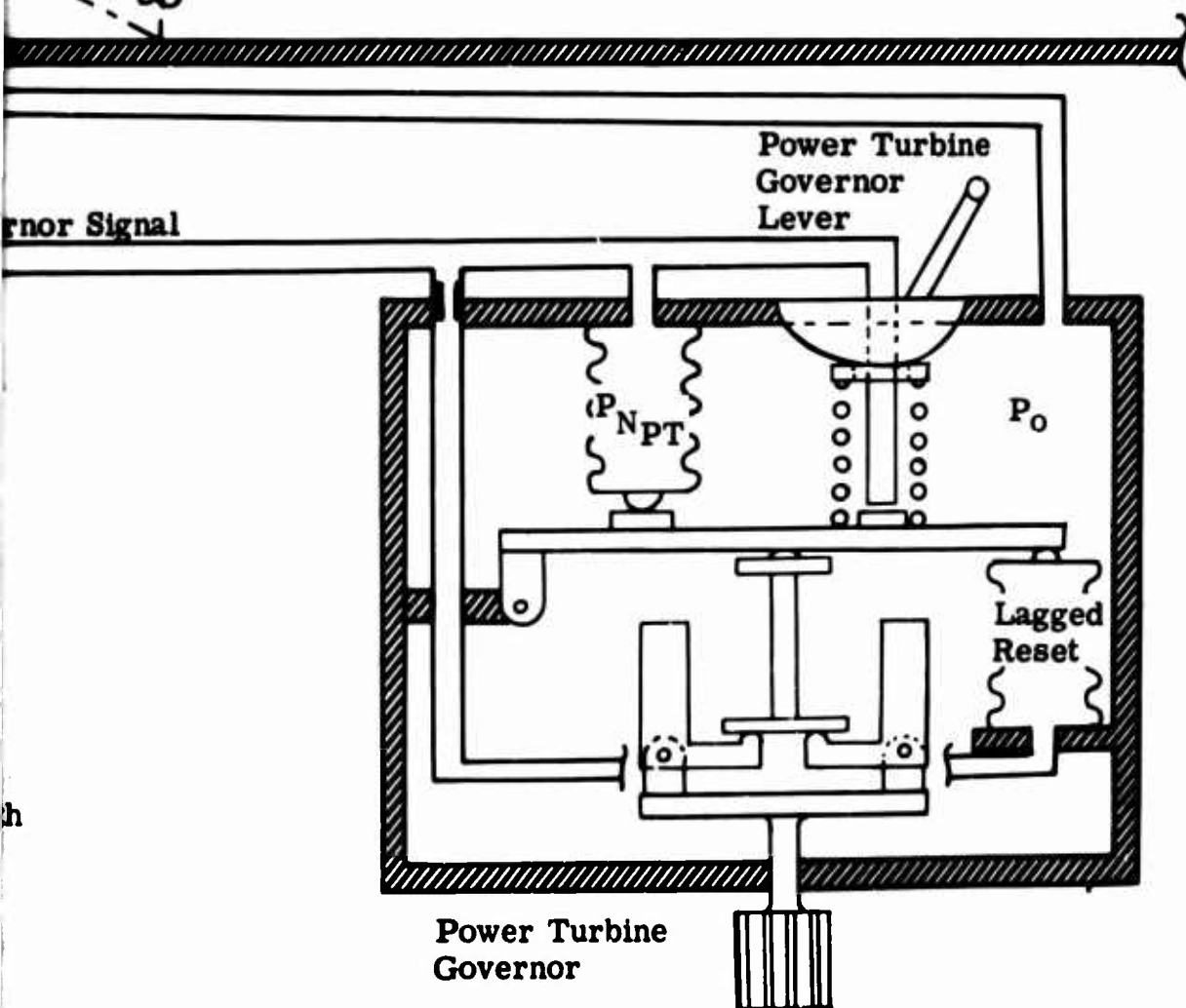
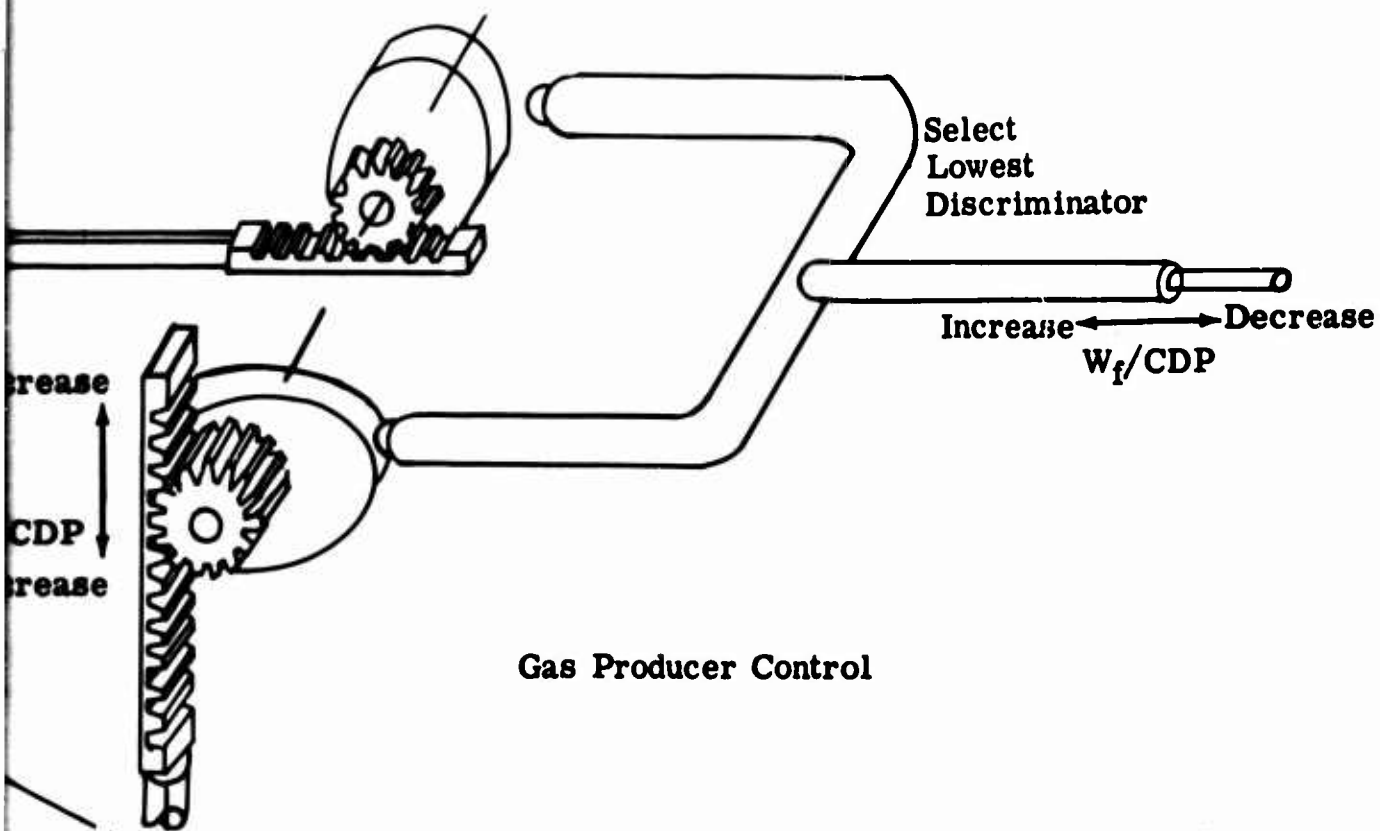


Figure 19. Schematic of the Lagged Reset Governing System With Separate Power Turbine Governor Component (Reset Governor).

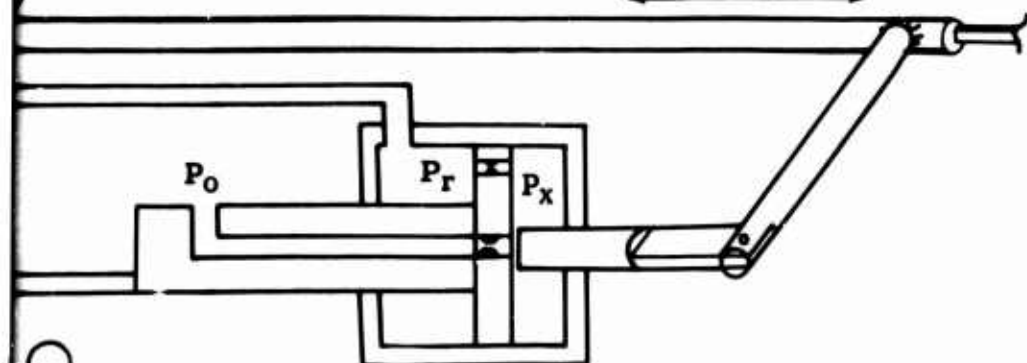
A



B

Gas Producer Control and
Power Turbine Governor

Increase W_t/CDP Decrease



Reset Lag
Function

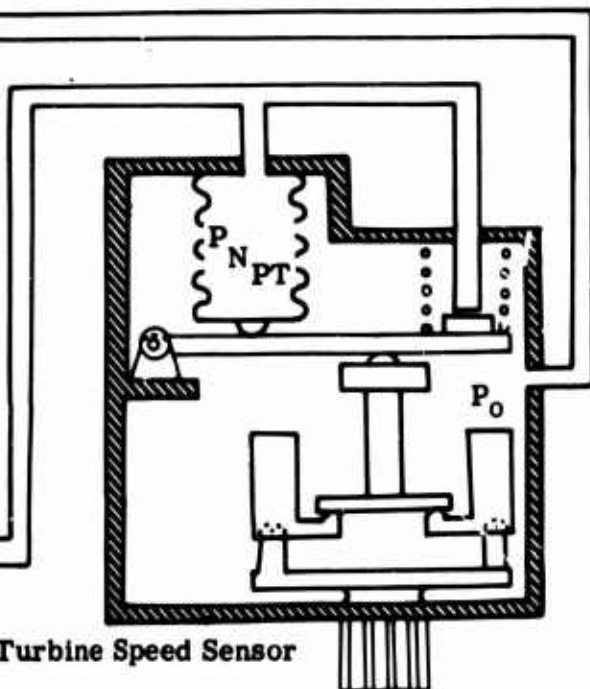
Power Turbine
Governor Lever



P_0

Power Turbine Speed Signal

Power Turbine Speed Sensor



B

Engines and controls in production will have certain performance variations because of manufacturing production tolerances. External control adjustments may provide the means for tuning each engine system so that it will operate at maximum performance, correcting for the production variations.

Similarly, the gas turbine engines and controls, when utilized in service, characteristically undergo performance changes. This is especially true when the systems are operated in an extreme environment or are subjected to an accelerated duty cycle. Control adjustments may be employed to achieve the maximum in-service operation of the aircraft, with the maximum engine performance available at all times.

An adjustment on the maximum gas producer governor speed setting is required so that military power will be provided.

The closed-loop turbine temperature limiter will prevent an overtemperature condition. However, it would not have the capability of overriding the gas producer control to increase the maximum governor setting if it is too low to reach military temperature. This is illustrated in Figure 17 to be an adjustable limit on the maximum travel of the gas producer control lever.

An idle gas producer governor adjustment may be necessary if the ground idle power requirements of the helicopter are critical. An external idle adjustment, if not provided, can be provided without complicating the control design. The decision as to its utilization is then based on the production and service experience of the engine.

Adjustment of the acceleration and deceleration fuel limit schedules is normally not allowed, because an improper adjustment of these schedules can result in hazardous engine performance at certain operating conditions, possibly resulting in damage to the engine and/or loss of total engine power while in flight. For this reason, external adjustments to these schedules are not provided.

EVALUATION OF MULTIENGINE GOVERNING-LOAD SHARING CONCEPTS

This evaluation resulted in the conclusion that a system with the following design features is required:

- Individual engine control governors with closed-loop load sharing on torque
- Collective-power turbine lever coordination (anticipation)
- Malfunction detector based on differential among gas producer speeds for selecting emergency

This system is defined in more detail in the section "Definition of an Optimum System."

The basic objective of this effort was to establish a governing-load sharing control system design. This will relieve the pilot of the responsibility of monitoring and regulating the performance of multiple engines during helicopter transients and critical flight maneuvering. The specific requirements of this control system related to the multiengine helicopter are as follows:

- Maintain a balanced load sharing between engines
- Provide stability in governing throughout the power range
- Provide rapid transient response to load changes
- Perform correctly with any engine(s) shut down
- Provide automatic power recovery in the event of an engine malfunction

The following paragraphs summarize the analyses that were conducted in the multiengine control system evaluation. This includes open-loop load sharing accuracy, individual governors with closed-loop load sharing, single governor with open-loop load sharing, automatic power recovery with an engine out, and constant rotor speed control.

OPEN-LOOP LOAD SHARING ACCURACY

In the multiengine helicopter studied, the output shafts of all engines are mechanically connected so that they operate at identical speeds. The helicopter load (power demand) is imposed on the engines as a net load, with the engine controls determining the power sharing split between the individual engines while performing their major role of governing the rotor speed. The open-loop analysis was directed toward establishing the accuracy of power matching that would be experienced in a multiengine

helicopter when not employing a special load sharing control. The affecting factors that were considered are engine and control variations in production and field service.

Engine Variations

Allison's production test data were utilized in establishing the gas turbine engine variations in production. This data accumulation and analysis was completed in a previously conducted USAAVLABS sponsored program (Heavy Lift Helicopter, Contract DA 44-177-AMC-213(T)).

The data accumulated relative to the T56 and T63 production engine performance variations indicate that these engines possess a similar power variation in production. For the T56, this is a maximum of 10 percent of point total variation in power level at a specific fuel flow. For the T63, this is a maximum of 10 percent of point total variation in power level at a specific gas producer speed (Figure 21).

The variation in the gains of power with fuel flow or gas producer speed was found to be small—equivalent to approximately ± 1.5 percent of maximum power in the minimum power range (Figure 22). This characteristic is true for both the T56 and T63 engines. A review of this information indicates that the power gain variation shown in Figure 22 is small and is typical of that which will be experienced with the type of engines to be employed in the multiengine powered helicopter.

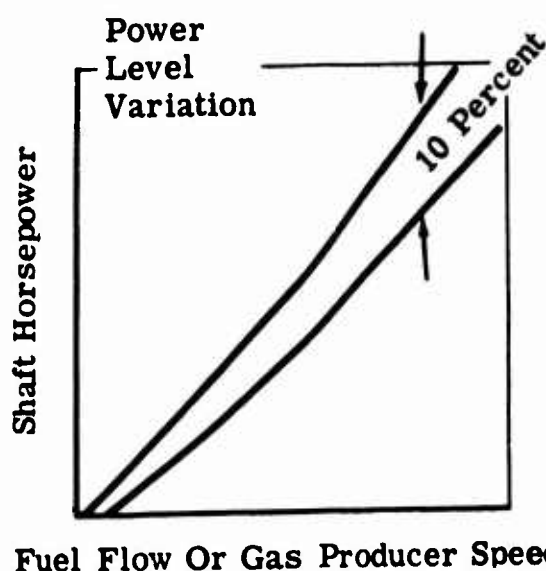


Figure 21. Power Level Variation.

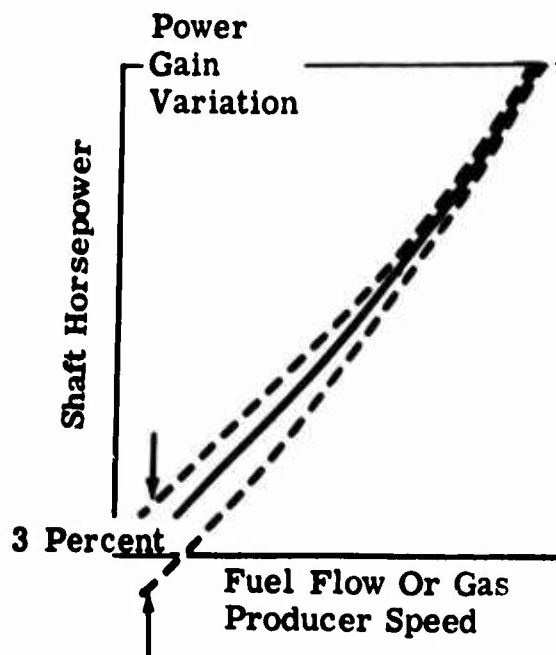


Figure 22. Power Gain Variation.

Control Variations

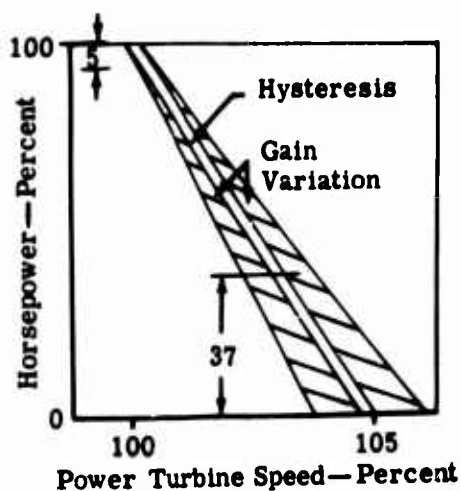
An engine control manufacturer (Bendix Products) provided the following 5-percent droop governor information defining the potential control system production variations for conventional hydromechanical controls:

- Power turbine governor gain— ± 14 percent of nominal gain
- Gas producer reset mechanism gain— ± 6 percent of nominal gain
- Governor hysteresis—0.25 percent of speed
- Power turbine lever-governor speed setting accuracy— ± 0.25 percent of speed

These data were utilized in the analysis of three control configurations. These configurations are as follows:

- Reset governing with individual governors
- Reset governing with a single governor
- Direct fuel governing with individual governors

"Reset" refers to the fact that the power turbine governor develops a signal which effects the fuel metering through a reset action in the gas producer control. "Direct" refers to a power turbine governor that is coupled in the fuel line between the gas producer control and the fuel nozzles,



**DIRECT FUEL
GOVERNING WITH
INDIVIDUAL GOVERNORS**

Figure 23. Reset Governing With Individual Governors.

**RESET GOVERNING
WITH SINGLE
GOVERNOR**

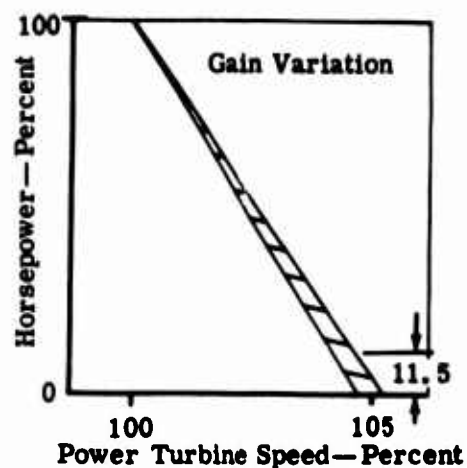
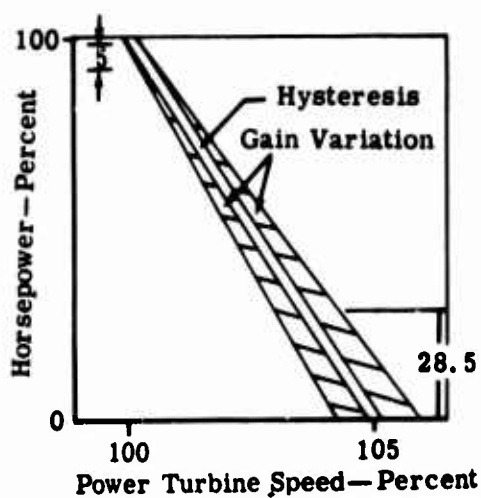


Figure 24. Reset Governing With Single Governor.



**RESET GOVERNING
WITH INDIVIDUAL
GOVERNORS**

Figure 25. Direct Fuel Governing Individual Governors.

directly affecting the fuel flow. Figures 23, 24, and 25 indicate the power matching accuracy characteristics of these three configurations. These data are based on a 5-percent steady-state droop governor design.

The variations indicated by Figure 23 include the effects of hysteresis, the governor gain variations, and the reset mechanism variations. This defines the total potential variation with reset governing and individual power turbine governors for each engine. Figure 24 illustrates the potential improvement by utilizing the single governor concept wherein one power turbine governor resets all gas producer controls equally and simultaneously. This illustrates the effect of eliminating the governor hysteresis and the governor gain variations as variables between engines. Figure 25 defines the potential differences with direct fuel governing and individual governors. This includes hysteresis and governor gain variations but does not have a reset gain variation.

Another important control variation that can affect the accuracy in a collective lever-power turbine lever reset configuration is the governor setting variation. The potential production control variation in the governor speed setting at a power turbine lever position has been defined as 0.5 percent (± 0.25 percent). With a 5-percent droop governor design, this is equivalent to a 10-percent power variation. Again, this effect would not be experienced with the single governor concept.

Power Variations

The engine and control system production variations must be combined in order to arrive at the potential total power mismatch that would be experienced with open-loop load sharing. The power level variations between engines can be adjusted out in the rigging of the engine or by pilot trimming of the governor settings, and can be excluded as an inaccuracy factor. Similarly, the power turbine lever-governor speed setting differences can be minimized by this procedure. The engine gain variations, however, cannot be adjusted out.

From a probability standpoint, it is not reasonable to sum all of the potential control variations and the engine gain variation effect in determining the total power unbalance which might occur. Table X presents the potential system differences. The total control differences are computed to be equal to the square root of the sum of the squares of the individual variations.

These data define the general magnitude of power unbalance that can occur with open-loop load sharing in a multiengine configuration and indicate the improvement that is possible with the single governor concept. To reiterate, this is because the majority of the potential control variations are

TABLE X		
POTENTIAL SYSTEM DIFFERENCES		
Governor Concept	Power Level	Total Power Variation (Percent)
Individual Governors, Reset Governing	Maximum	10
	Minimum	38
Single Governor, Reset Governing	Maximum	0
	Minimum	11.5
Individual Governors, Direct Governing	Maximum	10
	Minimum	35

associated with the high gain component, the power turbine governor. The use of a single governor eliminates the effect of production variations of this component on the load sharing.

INDIVIDUAL GOVERNORS WITH CLOSED-LOOP LOAD SHARING

This effort involved the evaluation of load sharing parameters, determination of a closed-loop load sharing control functional design, and investigation of the performance of the multiengine system.

Load Sharing Parameter

If all engines and sensing systems of a particular engine model were identical in their performance (shaft horsepower, turbine temperature, gas producer speed, fuel flow characteristics), there would be no operational advantage of one engine parameter over another for closed-loop load sharing control. However, the engine characteristics do vary in production and field service. For this reason, an evaluation of different engine parameters for closed-loop load sharing control was conducted.

In engineering meetings with helicopter companies, it was determined that the basic reasons for maintaining matched operation of the multiple engines were as follows:

- To satisfy the pilot that the engines are performing properly
- To enable proper red line limiting of the net torque by the pilot
- To minimize recovery time in the event of an engine malfunction
- To obtain maximum life of the transmission system parts

It is concluded that the torque parameter is satisfactory for all cases and does not impose any engine or helicopter performance characteristics that are operationally unacceptable. The closed-loop sharing control, therefore, should utilize the torque parameter for engine matching.

Torque

The consulted helicopter companies indicated that the preferred engine parameter to be matched or balanced is torque. The pilot monitors the torque indicator(s) to determine if the engines are performing satisfactorily. Mismatch between the torque indicators of different engines create the impression that the engine system is not performing properly. With torque as the parameter for closed-loop load sharing, any differences between engine indicator readings will signal the pilot that special precaution may be required in selecting higher power demands. The torque mismatch may be due either to an incorrectly performing engine or control or to an engine's reaching its maximum power level.

In helicopter designs which do not employ a transmission net torque-meter, matching on the torque parameter would make limiting to the red line less difficult. Since all engines are at the same torque level, the indicator would essentially indicate the net torque relative to the red line. (This is true for all operations except for the case where an engine is limited by the turbine temperature limiter.)

In some multiengine helicopter transmission designs, unbalance in the input torques can affect the endurance life of the power transmission system. One helicopter company indicated that zero torque unbalance at the maximum power conditions was required to obtain the maximum endurance life. Another consideration was associated with high power operation. Matching on torque would result in unbalanced turbine temperatures, with one engine operating at a higher temperature than the others. If the helicopter loading had to be manually restricted to prevent excessive turbine temperatures on the high temperature engine, the system would be operated at below maximum capability. However, with the employment of the automatic turbine temperature limiters on each engine, this problem is eliminated.

In general, it is concluded that there is no significant disadvantage of the torque parameter, and operationally it is desirable. (This is assuming that an automatic turbine temperature limiting system is employed.)

Turbine Temperature

Matching on turbine temperature was evaluated to determine if this might provide an increase in the service life of the engines (and on-duty time of the aircraft) or an improvement in the operational characteristics of the multiengine system.

One factor affecting the endurance life of turbine components is the turbine temperature level effect on the metal creep rates. This effect, however, is not related to the normal engine power deteriorations that occur in field service, but instead affects the turbine structural integrity. The power depreciations are more normally associated with compressor deterioration (i.e., erosion, corrosion, seal rubbing, etc). This occurrence in many cases determines the overhaul life of the engines. If all engines are maintained within their operating turbine temperature limits, the metal creep rates will not be excessive, and the guaranteed turbine life can be realized. Turbine temperature matching in the multiengine system would reduce the metal creep rate on a low power engine, reducing the rate of decay of structural integrity. However, unless an engine duty cycle analyzer (e.g., time-temperature totalizer) is employed, there would be no way of realizing the extended service life of which the hot section parts are capable. The duty cycle analyzer would be required to provide a record of the time-temperature history of each engine to be used for determining the endurance life limit.

Performance analysis indicated that this parameter would not enable proper control and matching in the low power range. Many free turbine engines possess a characteristic reversal in the turbine temperature-fuel flow (or power) relationship at low powers. This shallow or reversing gain characteristic (Figure 26) will not allow proper closed-loop matching. A control designed to operate with the engine gain characteristic ($\Delta T_t / \Delta W_f$) at high power would be incompatible with the reversed (or shallow) characteristic at low powers. The result would be instability or improper control in the low power regime.

Gas Producer Speed or Fuel Flow

Matching on either gas producer speed or fuel flow would be acceptable from an engine standpoint and would enable effective compensation for control system differences. However, neither parameter will provide compensation for torque differences between engines because of production tolerances or deterioration in field service. Except for this factor, matching on either gas producer speed or fuel flow could be employed.

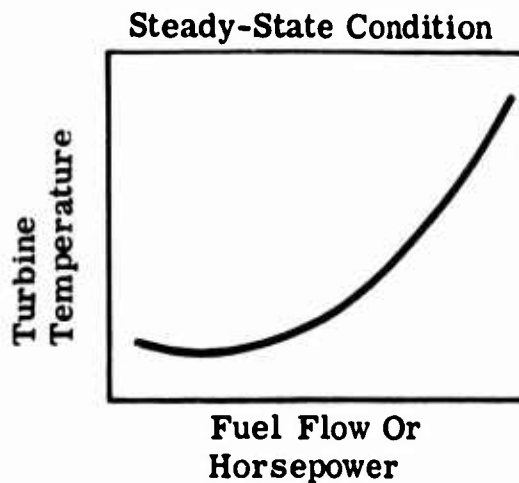


Figure 26. Typical Free Turbine Engine Steady-State Characteristic.

Closed-Loop Load Sharing Control

The basic requirements for a closed-loop load sharing control have been defined. A control mode study was conducted, resulting in the definition of a control functional design.

Control Requirements

The control must utilize engine torques as the controlled parameter, with the output signal of the control trimming the power turbine governor speed settings. Studies previously conducted have indicated that the authority that must be delegated to the load sharing control can be minimized by this approach because the governor is a high gain device. With this approach, the load sharing control action would never limit the power availability but would alter the rotor speed-power relationship. This is desirable when considering malfunctions in the load sharing control loop since their effects are minimized.

As part of the basic requirements, certain conditions were defined which the load sharing control must handle. The conditions requiring proper control are as follows:

- With any engine turned off
- With malfunction of any engine losing power

- In power transients
- During turbine temperature limiting

When an engine is turned off, the load sharing system should continue to perform its function, preferably with no rotor speed change. With an engine malfunction, the load sharing control should continue to control and the rotor speed should not be changed. (A signal from a malfunction detector may be required to provide a lead in engine demand, minimizing the steady-state and transient rotor speed droop.)

During the power transients, the control should not slow down the fast-responding engines to match the slower one. It would, instead, speed up the slower one if any load sharing control action is provided in power transients. The load sharing action must never limit the power availability. If one engine encounters and is controlled by a turbine temperature limiter or gas producer speed limiter, the power available from the other engine should not be limited to that of the low power engine. These are the basic requirements that were established for the load sharing control.

Control Mode

The control mode selected is based on the master or reference torque from the highest torque engine, rather than an average torque or a fixed predetermined master. In this concept, the power levels of the low engine are effectively increased to match that of the high engine, with the governor action adjusting the net power level to match the requirements of the load. Utilizing the highest torque engine as the reference is desirable when considering engine power failures, power depreciation, or operation of an engine which is turbine temperature (or gas producer speed) limited. The results are that the low power engine cannot have an effect on the governor settings of the other engines, and the control system will tend to provide the maximum available power at all times.

The average torque concept is one wherein the reference would be computed as an average of all engines. Conventionally, this reference would be compared to each individual engine's torque signal; the resulting difference signals to be employed to set the governors of the high engines down and the low engines up. This approach would not provide proper load sharing and power control with an engine reduced to idle or shut down, or with the occurrence of a power failure of an engine. Additional control functions would be required to modify the control computer during this type of operation so that the computation of the average torque will be based on

the actual number of engines supporting the load rather than on the total number of engines in the aircraft. The result would be a more complex load sharing control. This is not as desirable as the highest torque master concept.

The fixed master concept would utilize the torque signal from one specific engine as the reference, regardless of its relative torque level. A disadvantage of this approach is that if the selected master was the lowest torque engine (either due to its governor setting or being temperature limited), the load sharing action would be lost. A pilot-operated switch would be required to allow selection of a new master reference. This manual selection would not be as desirable as the automatic selection provided by the highest torque reference concept. If the master engine encountered a power failure or was manually shut down, the load sharing control action on the other engines would also be upset. Unless the control system employed a malfunction detector system that provided automatic power turbine governor reset and/or changed the reference engine (along with emergency power capability selection), the slave engines would initially have their power levels reduced with the occurrence of the failure of the master engine. This would be unacceptable, especially if it occurred during a critical flight phase of the helicopter, e. g., hovering or landing. For these reasons, the fixed master concept is not as desirable as the highest torque reference concept.

Functional Design

The load sharing control functional design is based on the floating master concept, where the engine producing the highest torque is the master engine. As previously explained, this concept was selected to provide the desired performance with one engine shut down, with turbine temperature limited or gas producer speed limited, for increase power transients, and for a loss-of-power engine malfunction. The control would utilize the master torque signal for comparison with the individual torque signals of each engine to develop independent trim signals for each power turbine governor. Figure 27 illustrates the functional design of the control.

The trim signals generated would be proportional to the torque error and unidirectional to the extent that the power level could only be increased. The proportional scheduling is required with the floating master concept so that the high torque engine will always be in the zero trim position when it is the master. This provides a load sharing control that will simply and automatically zero out the governor trim on any engine when it takes over as the master. Operation of the master engine with zero trim of its

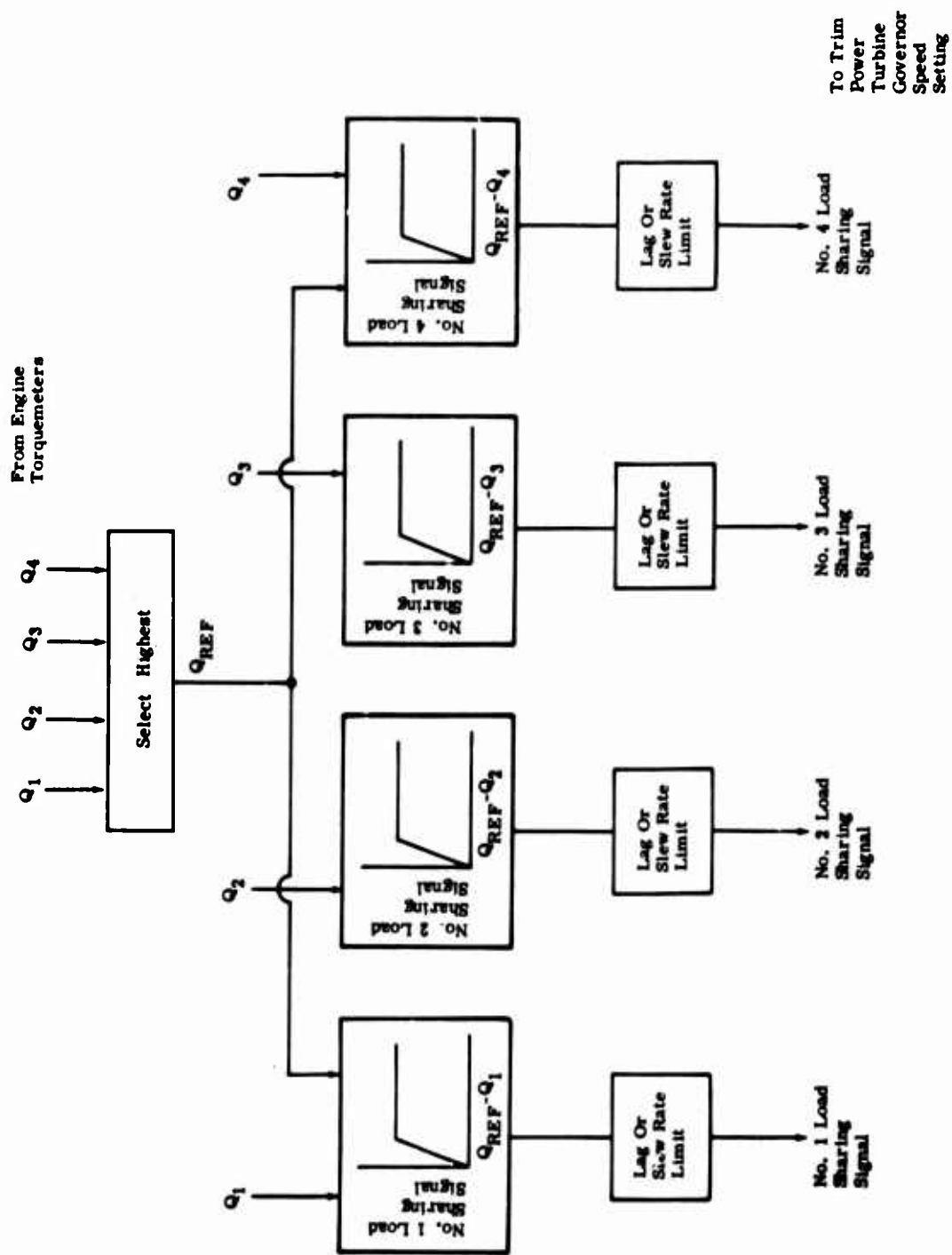


Figure 27. Closed-Loop Load Sharing Control Functional Design With a Four-Engine System.

power turbine governor is necessary so that the slave engines can effectively be matched to the master without requiring a large magnitude of governor trim. This characteristic is desirable since it minimizes the changes in governed speed caused by the load sharing control action. As a result of this design approach, the load sharing action will not reduce the torque difference between engines to exactly zero. However, the proportional gain can be high enough to make the torque difference quite small.

An integrating load sharing control design was also considered which was capable of reducing the torque difference to zero. This design could be employed with the floating master concept. However, for this design to function properly a special zero trim function would be required to detect the master engine and to override the load sharing control of that specific engine in order to provide zero trim of its governor. Without this override, a change in engine master could occur during some condition, e. g. , a change in the load. Because the integrator on the master engine would receive a zero torque difference signal, it would not reduce its power turbine governor trim. The result would be an unacceptable shifting (increase) of the governed speed, and the load sharing action would eventually be lost. Because of the added control functions required with the integrating design to prevent this, it would be more complex than the proportional design. For this reason, the proportional design is the more desirable approach.

Load sharing control limits on the power turbine governor speed setting trim authority (magnitude) available to the load sharing control are required so that the effect of malfunctions in this control loop will be minimized. The minimum trim limit (which is zero) will prevent the control from selecting a low-speed setting, causing a low rotor speed and/or loss of power. The maximum trim limit will prevent the occurrence of a high-speed setting which might cause rotor overspeeding.

A dynamic function in the load sharing control loop may be required to maintain stability during steady-state operation. The purpose of this function is to prevent the load sharing control from responding to torque-meter signal noise and/or torsional oscillations. The dynamic function may be either a lag or a slew rate limit, depending on the detail design employed.

Mechanical Design

Figures 28 and 29 are schematics depicting combined load sharing control and power turbine governor designs for a four-engine system. These schematics are presented to indicate the type of mechanisms that would be required to accomplish this action.

Figure 28 is a hydromechanical design employing torque signals from hydraulic torquemeters and producing a hydraulic pressure output signal for use in the gas producer control. This involves a torque discriminator component utilizing a sequence of shuttle valves to select the highest torque engine for the reference signal. The reference signal is then transmitted to all power turbine governors.

Each of the hydromechanical governors performs the load sharing computation and governor speed setting trim, receiving the torque signal from its respective engine plus the reference signal. The power turbine governor design illustrated in Figure 28 is for the proportional governor with lagged gain reset. Each governor receives, as an input, a regulated servo pressure (fuel) from its gas producer control, and generates a pressure signal for the gas producer control to alter the metered fuel flow.

Figure 29 is an electronic design that would employ torque signals from electronic torquemeters and would produce an electrical signal for use by the gas producer control. In this design, each engine has a separate load sharing control, a power turbine governor component which receives all four engine torque signals. Each component performs the torque discrimination function plus the load sharing control computation and power turbine governor speed setting trim. This governor design is also based on the proportional plus lagged gain reset mode. The electrical output signal from the component(s) is then employed in the gas producer control to effect the fuel metering.

Another approach would be a combination electronic-hydromechanical design, where part of the computation is performed by electronic components and part by hydromechanical. For example, an electronic load sharing control may be employed with a hydromechanical power turbine governor. Design studies for a particular engine and system are required before the optimum configuration can be defined.

Multiengine Performance

The potential steady-state power unbalance without closed-loop load sharing and with individual governors has been defined to be 10 percent at

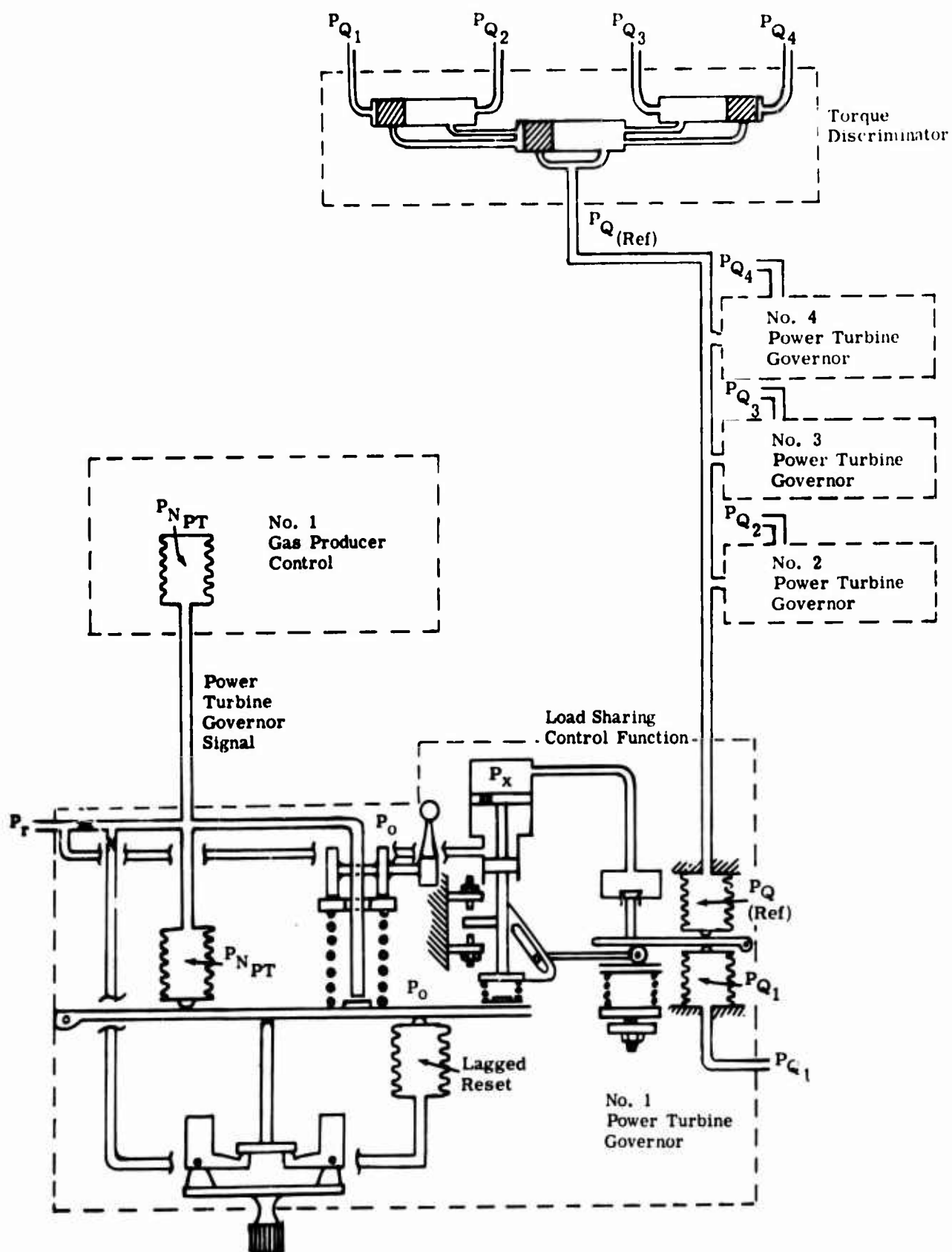


Figure 28. Schematic of Hydromechanical Load Sharing and Power Turbine Governor.

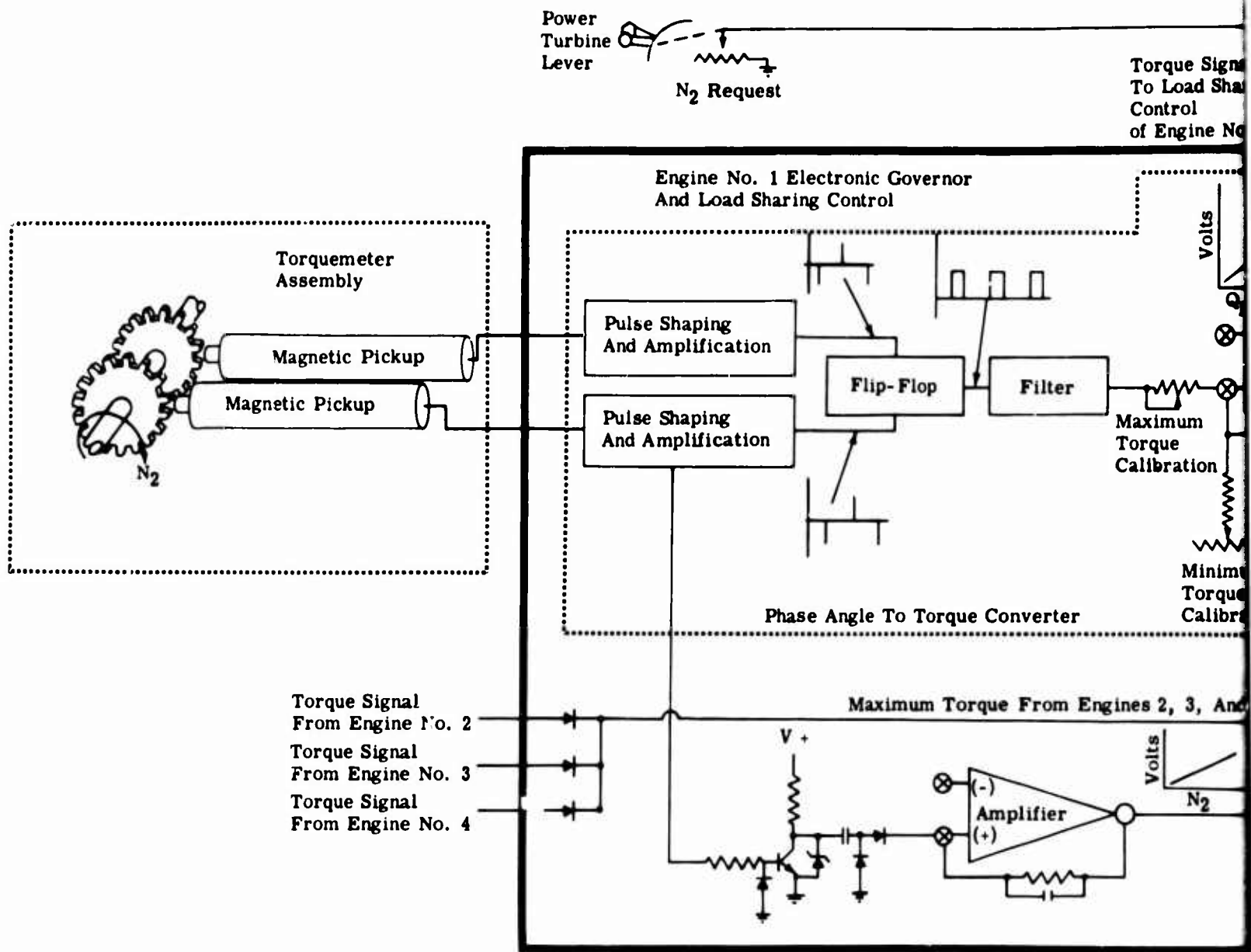
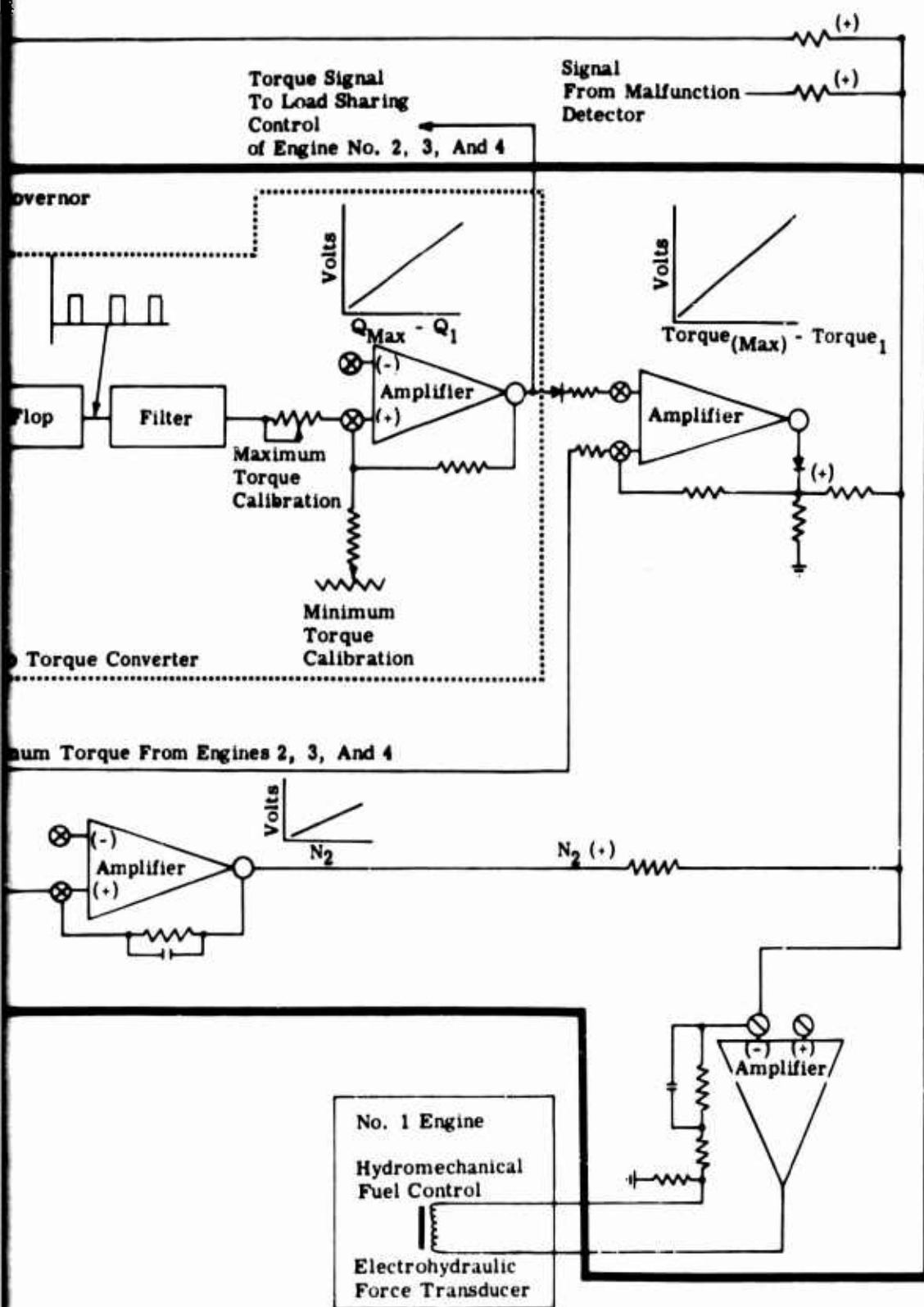


Figure 29. Schematic of an Electronic Load Sharing-Power Turbine Governor Control System.

A



B

maximum power and 38 percent at low power. (See Open-Loop Load Sharing Accuracy section.) Based on these data, assumed control characteristics were defined to be utilized in the investigation and evaluation of the closed-loop load sharing control design. Figure 30 defines the steady-state control characteristics that were assumed, including differences in the power turbine governor gains and the governor settings. These characteristics are included in the multiengine power system simulation (described in the "Generation of A Power System" section). The power turbine governor mode employed in this simulation is the direct fuel flow/compressor discharge pressure governor with lagged gain reset.

The following is a documentation of the multiengine system performance with individual power turbine governors, as affected by the load sharing control. This includes steady-state operation, stability, and transient operation.

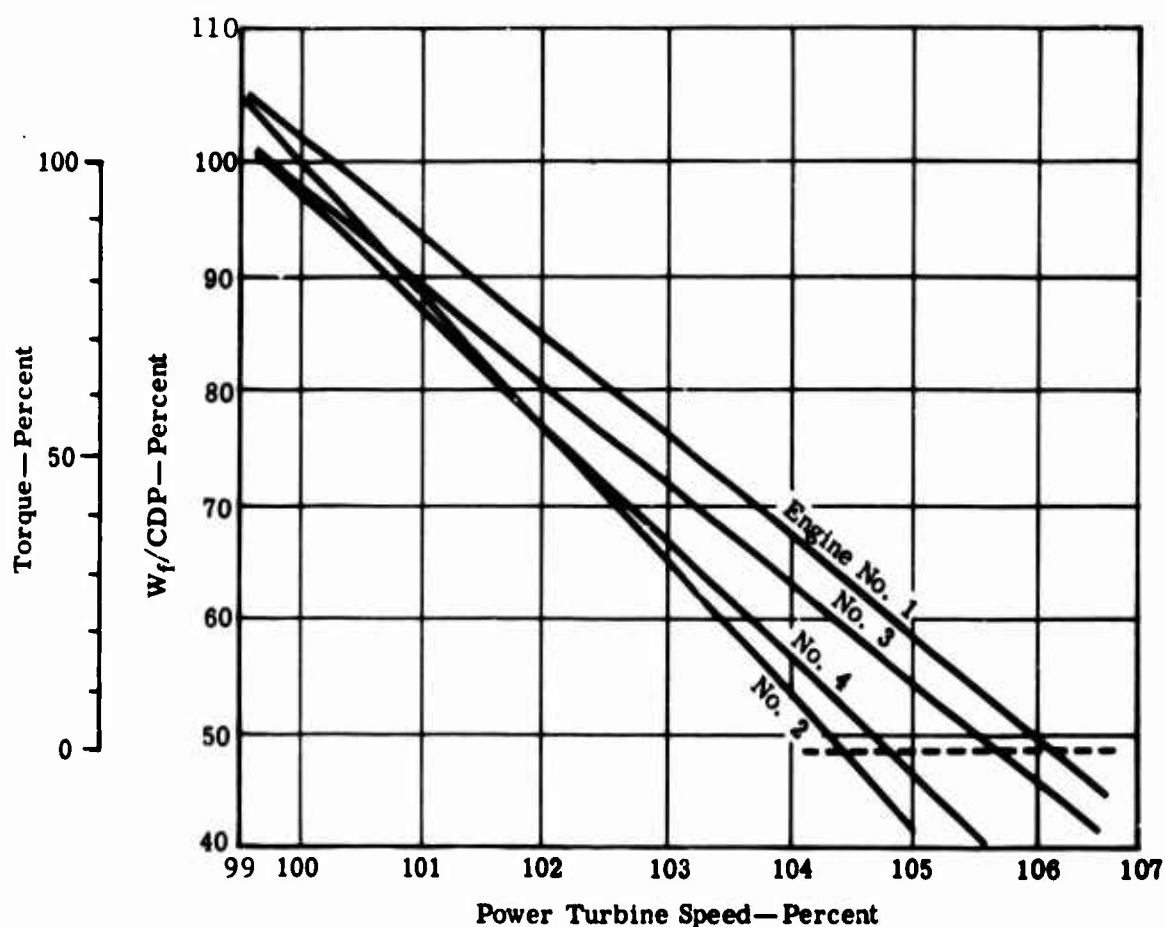


Figure 30. Assumed Control Characteristics With Individual Governors.

Steady State

The proportional load sharing control design selected, which was previously noted, will not reduce the steady-state torque differences to zero. The magnitude of the steady-state torque difference with load sharing control is dependent upon the following:

- The proportional gain of the load sharing control
- The gain of the power turbine governor(s)
- The torque difference between engines without load sharing control trim
- The magnitude of power turbine governor trim authority allotted

The power turbine governor design selected has a nominal gain that will result in a 5-percent speed change from 0- to 100-percent power, at a fixed governor speed setting. Figure 30 illustrates the steady-state torque differences between engines without the load sharing control that were deemed possible and must be contended with. Figure 31 defines, for this configuration, the effect of load sharing control proportional gain on the maximum steady-state torque difference between engines.

These data indicate that a control gain in the range of 1.0 to 2.5 would be quite adequate, providing a torque difference of less than 0.5 percent at maximum power and less than 2.0 percent at low power. (The control gain is defined herein as the ratio of power turbine governor speed setting trim to torque error (ΔN_2 trim/ ΔQ error), in units of percent/percent.) Higher control gains are not desirable, since they would make the load sharing control loop more sensitive to sensor or control noise, hysteresis, and/or lags. For this reason, the gain should be as low as possible to be consistent with the required torque balancing accuracy.

The power turbine governor trim authority limit is required, as previously explained, to provide a limit on the authority of the load sharing control. This trim authority should be maintained at a minimum consistent with the requirements for load sharing control. Figure 32 defines the effect of encountering the power turbine governor trim limit on the steady-state torque difference, based on the previously defined governing configuration. These data indicate that a trim (ΔN_2 trim) authority of 2.1 percent is required so that it will not interfere with the load sharing control, which is based on a control gain in the 1.0 to 2.5 range. A lower authority limit is not desirable since its action would effectively limit the load sharing control, causing large torque differences at low-power conditions. For example, a 1.5-percent trim limit would result in a torque difference of greater than 10 percent when operating with a 23-percent load.

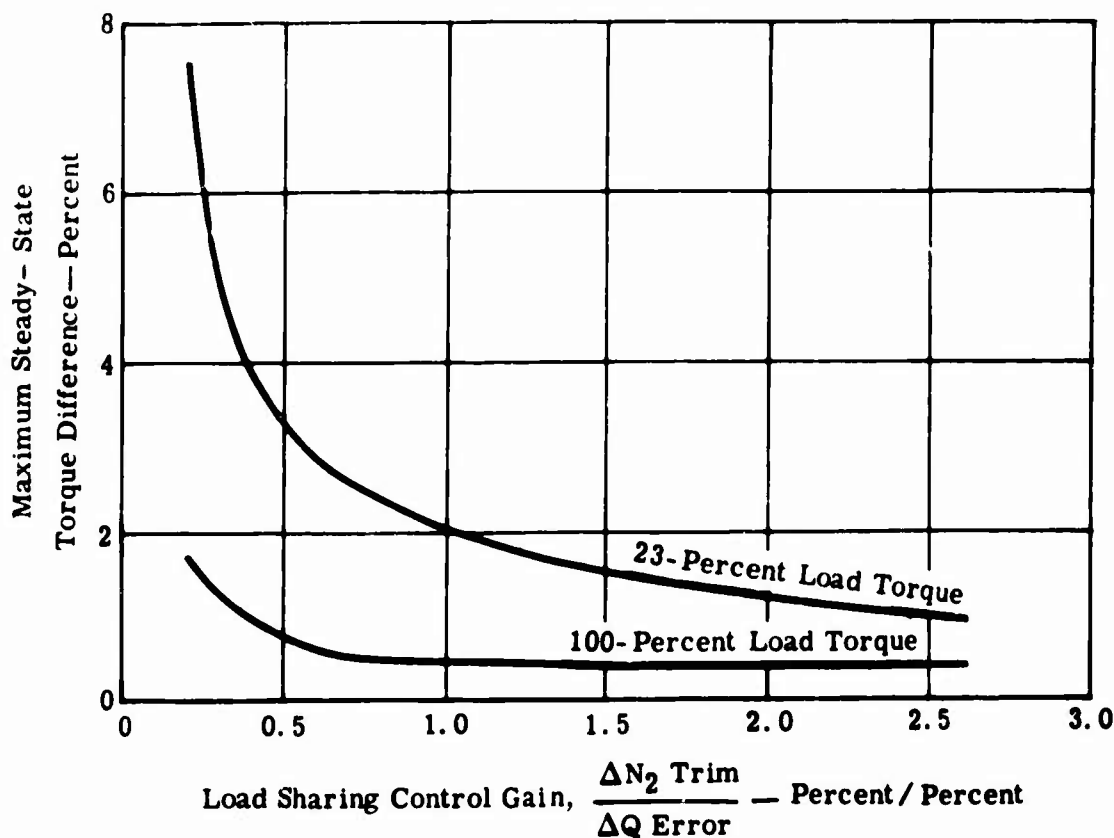


Figure 31. Effect of Load Sharing Control Gain On The Steady-State Torque Unbalance.

The data in Figures 31 and 32 are for the governor configuration illustrated by Figure 33. If a governor of a different design gain (steady-state droop) is employed, the required load sharing control gain and governor trim limits may be somewhat different.

In an autorotative (zero net torque) condition, all engines will be operated at zero torque, and decoupled from the helicopter transmission-rotor system. In this condition, the load sharing control will automatically select zero governor trim on all engines because of the zero torque difference.

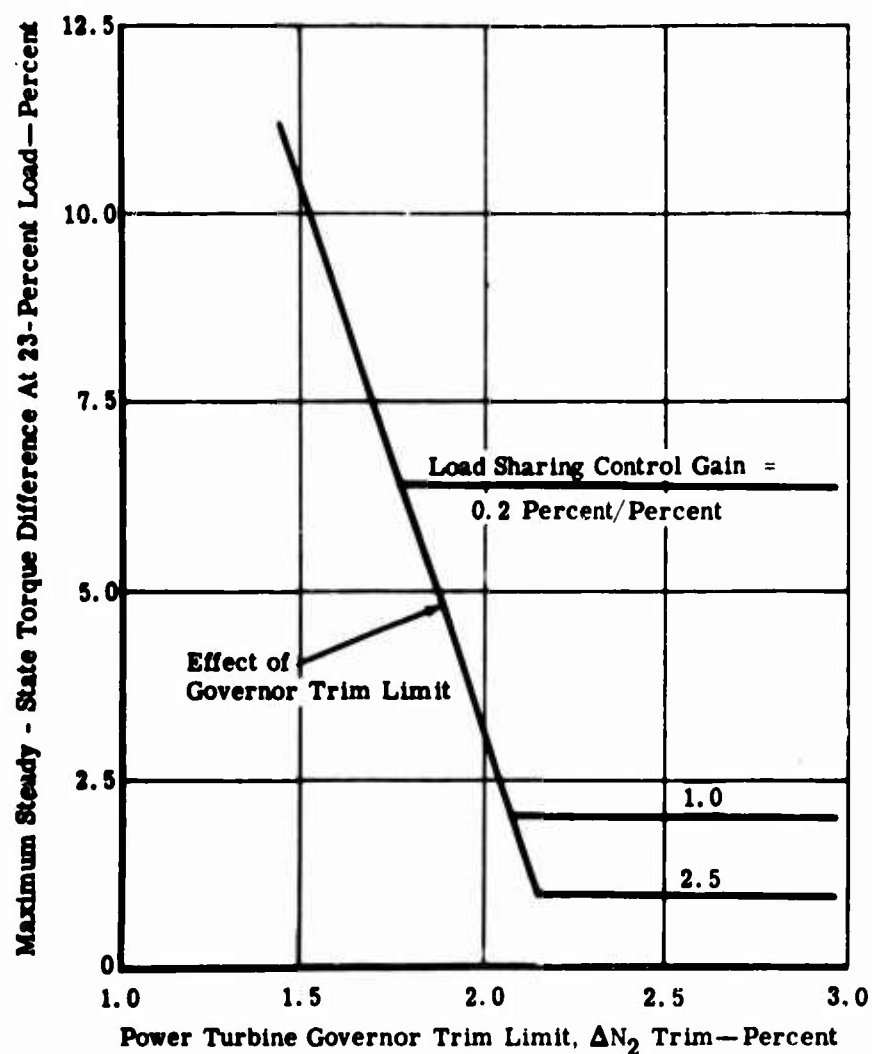


Figure 32. Effect of Load Sharing Control Design Variables On Steady-State Torque Unbalance.

The result will be that each power turbine governor will be individually controlled and governed at slightly different speeds, depending on the differences between the systems. For example, the four-engine system that was simulated would result in the following power turbine speeds when decoupled and governing:

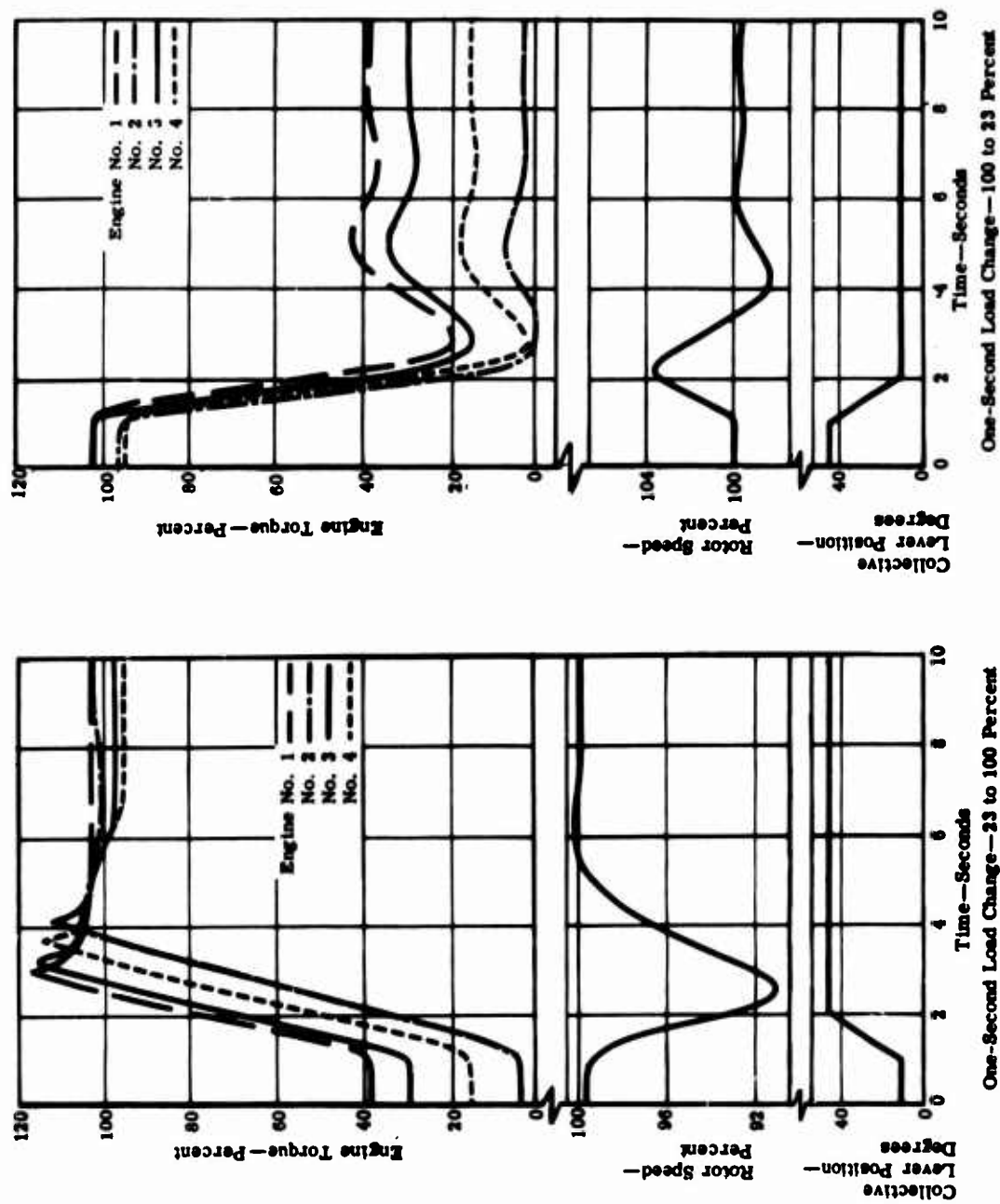


Figure 33. Transient Performance With Individual Governors Without Load Sharing Control.

<u>Engine Number</u>	<u>N₂ (Percent)</u>
1	101.6
2	98.5
3	101.1
4	99.5

The result will be approximately a 3-percent maximum difference between turbine speeds when operating with all engines decoupled. This operation should be quite satisfactory.

Stability

The stability of the individual governor system was evaluated, utilizing the multiengine power system simulation. This involved imposing a step change at different power levels and observing the system response in terms of engine torque(s) and helicopter rotor speed.

The governor system design data (gains and dynamics) employed in this evaluation were those established by the Bode and analog linearized stability analyses conducted in the section on Evaluation of Power Turbine Governing Modes. The stability investigation utilizing the nonlinearized (full scale) simulation demonstrates that in a multiengine system the control system design selected is stable throughout the power range, with or without the load sharing control in operation. No significant difference in the stability performance was found between a two-, three-, or four-engine power system configuration, or with one engine in the system shut down or at ground idle.

Figure 34 presents the stabilization characteristics of a four-engine system when subjected to the step load changes. On a 91- to 100-percent torque load change, the system indicates stabilization after one undershoot and overshoot in rotor speed, with or without the load sharing control operative. This characteristic is indicative of a well damped governing system. The resulting engine torque characteristic also indicates that the torsional excitation associated with a step collective lever load change is not supported by the engines (control system). They are dissipated by the inertial and aerodynamic damping.

Similarly, on a torque load change from 16 percent down to 12 percent, the rotor speed stabilization occurs after one overshoot and undershoot. In

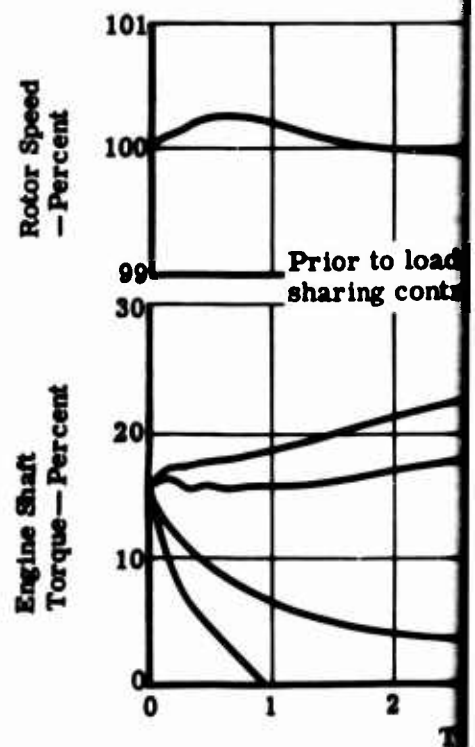
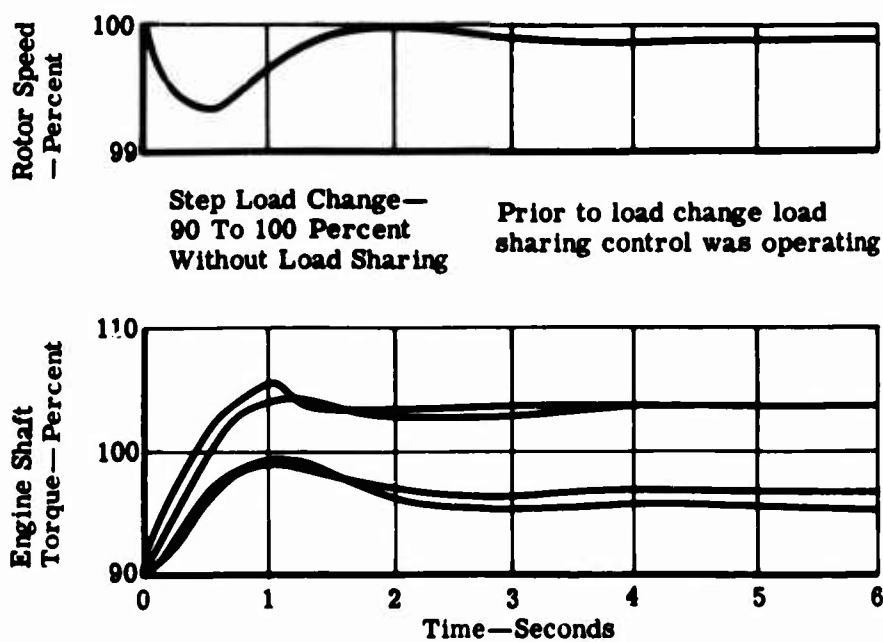
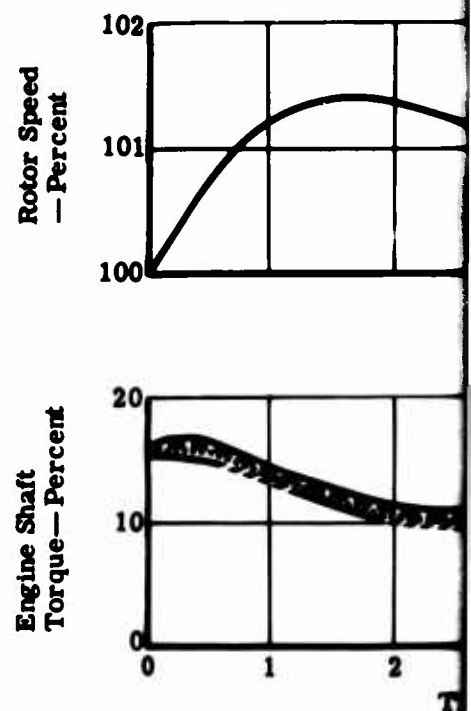
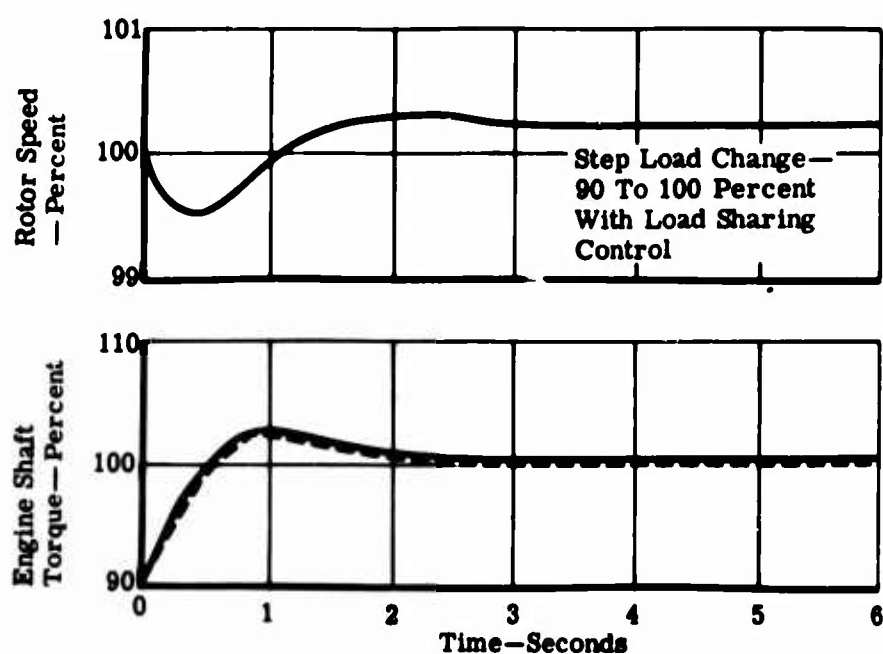
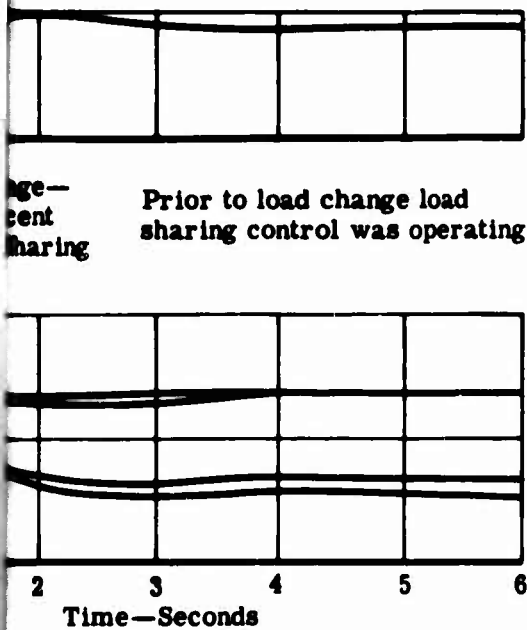
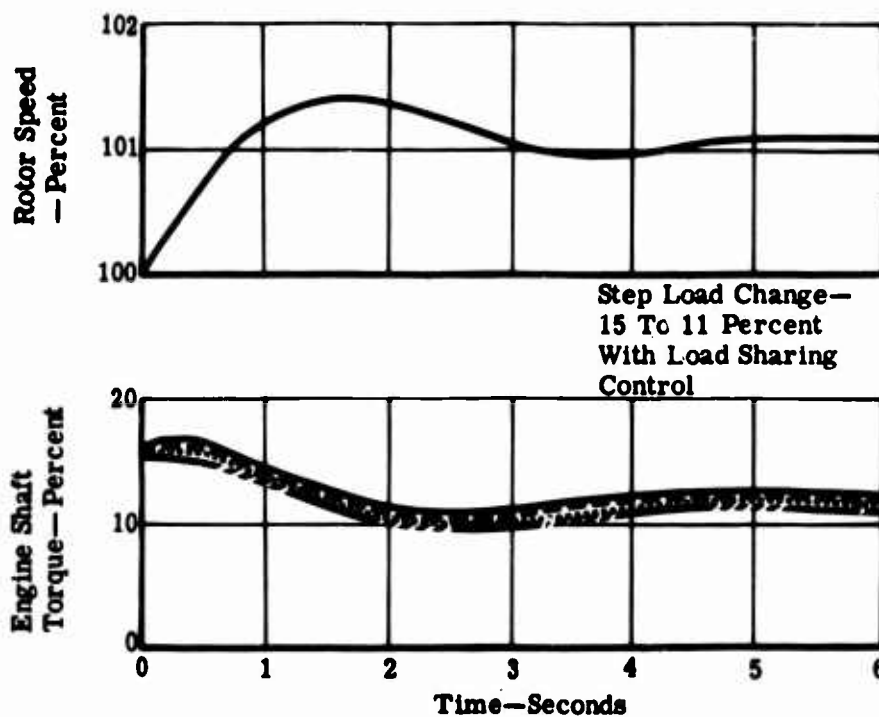
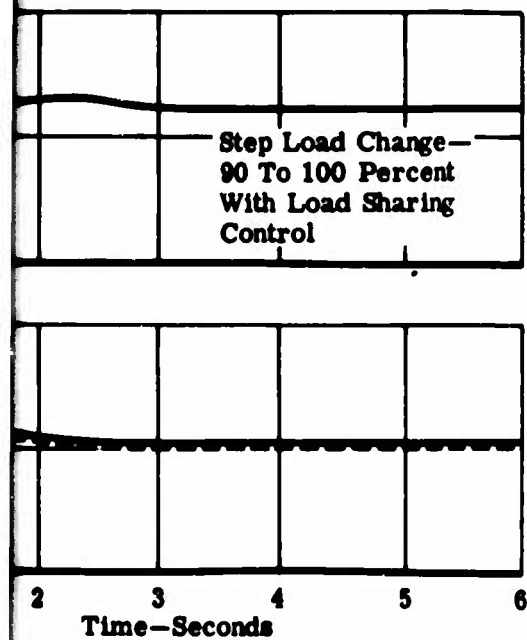


Figure 34. Stability With and Without Load Sharing—Four Engines.

A



With and Without Load Sharing—Four Engines.

B

this case, the torsional excitation is initially evident in terms of engine torque because of the very low aerodynamic damping but, again, is dissipated because the control system does not support the torsional. At this low power condition with the load sharing control inoperative, the number one engine decoupled because of the differences between governor settings and gains.

Stability checks were also made with three- and two-engine configurations, indicating that there is no discernible difference in their dynamic characteristics and those of the four-engine system.

A four-engine configuration with one engine shut down and a two-engine system with one engine shut down were investigated and found to be stable. These runs indicated two overshoots and one undershoot in stabilizing, again performing like a well damped system.

With the load sharing control in effect, a slightly higher rotor speed (1 percent or less) occurs at stabilization, as compared to the case without load sharing. This is due to the load sharing control trimming action on the power turbine governor and the large difference between controls (settings and gains) that is employed in the simulation. (This effect is overemphasized in Figure 34 due to the expanded speed scale.)

Figure 35 illustrates the stability in governing when the power turbines decouple from the helicopter rotor system (autorotation), with and without the load sharing control operating. These data indicate that the power turbine speed governing stability would be very good. In the decoupled condition, the torquemeter would sense zero torque on all engines and would provide no load sharing action (zero governor trim). This is the reason why the power turbine stabilization speeds are the same for the load sharing control operative or inoperative. The effect of the load sharing control is indicated in the speed at which decoupling occurred in the transient.

Power Transients

The transient response and performance of the individual governor system were evaluated, utilizing the multiengine simulation. This consisted of imposing different types of collective lever load changes on the system and of observing the power system performance in terms of engine torque(s) and rotor speed. Torque is of importance since it indicates the load sharing during power transients. Rotor speed provides an indication of the multiengine system's overall transient performance, indicating its quality of rotor speed control.

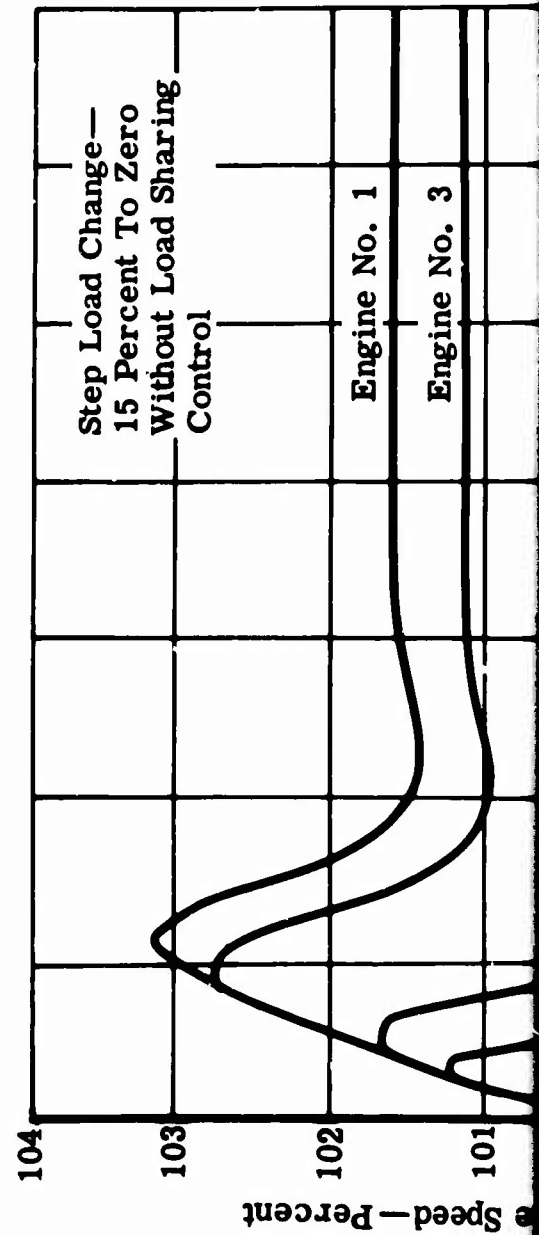
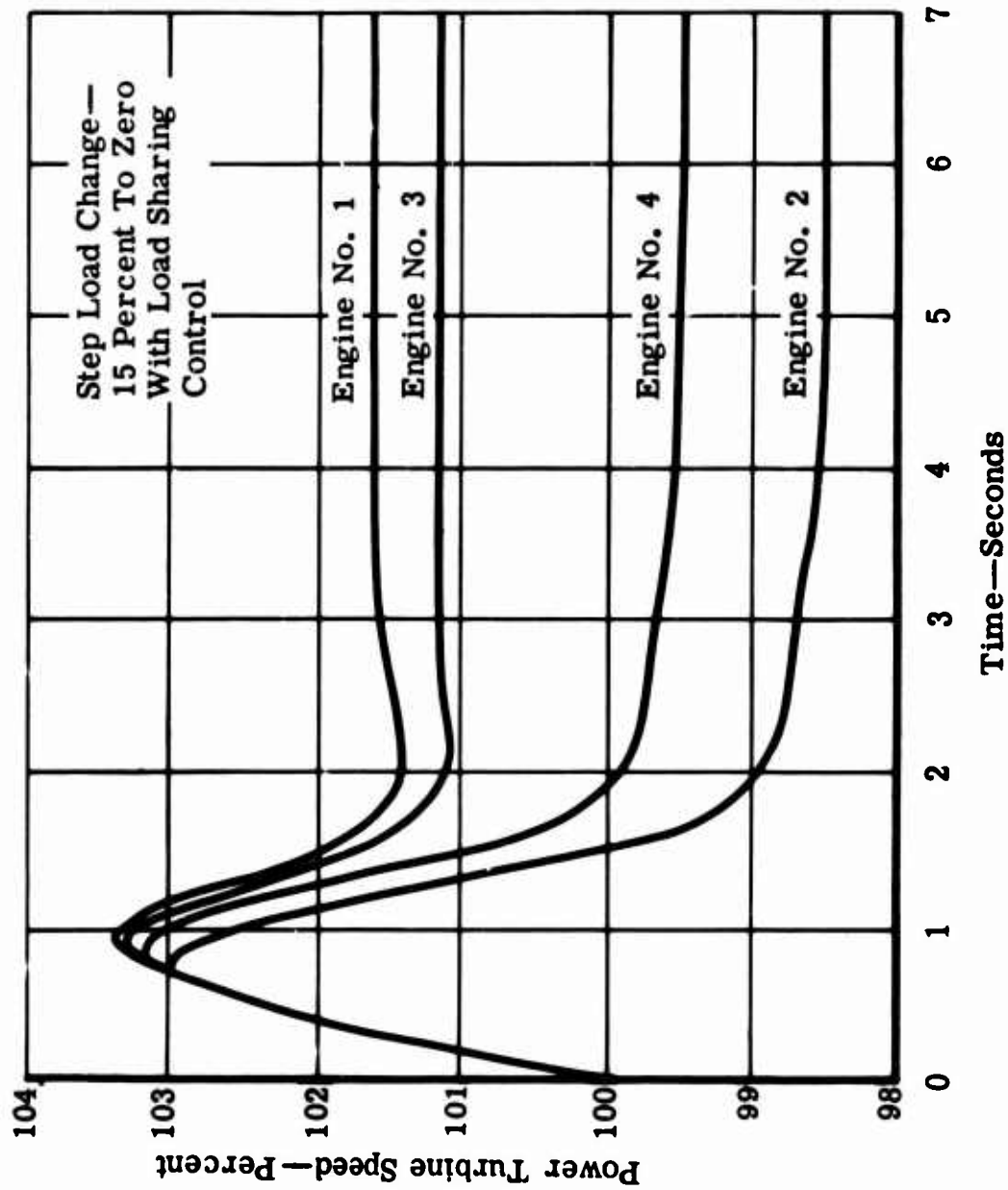
The load transient evaluation indicated that the governor and load sharing control designs were satisfactory. This evaluation included transients with and without the load sharing control in operation, with different load sharing control gains and dynamics, with different load changes and change rates, and with different numbers of engines in the system.

The control system configuration employed in this evaluation utilizes the fuel flow/compressor discharge pressure with lagged reset gain power turbine governor mode. The steady-state gain was one which would result in a 5-percent power turbine speed change from maximum power to zero at a constant power turbine lever angle. Collective lever-power turbine lever coordination was employed to effectively provide steady-state governing to a constant power-turbine speed through the power range.

Table XI summarizes the transient performance characteristics of this system. Transients over other power ranges were also investigated, but the 23- to 100-percent load range was selected for the comparative evaluations as being typical. Configuration A in Table XI defines the transient response capabilities of the basic helicopter rotor system and engine design employed in the analysis, excluding the effects of the governing control system. These data are defined herein to provide a base line to enable evaluation of the control system effects.

Table XI indicates that the governing and load sharing control system has very little effect on the maximum transient rotor speed droop during an increase load transient. This is because the collective-power turbine lever coordination effectively provides anticipation, forcing the fuel flow to be increased to the extent that the acceleration fuel limit schedule regulates the engine performance through the major portion of the transient. The load sharing control design can increase the power turbine governor setting (fuel flow) but cannot reduce the speed setting. Therefore, it cannot reduce the fuel flow below the acceleration schedule.

The governing-load sharing control system design can affect the peak transient rotor speed which occurs on a decreased load transient. This is because the deceleration fuel limit schedule of the engine and gas producer control employed in the analysis is very low relative to the gas producer steady-state required to run. The collective lever effect with coordination alone will not provide a fuel flow reduction large enough to cause operation on the deceleration schedule over the complete deceleration. The result is that during part of the deceleration, the power turbine governor affects the engine fuel flow. Because of this, and the fact that the load sharing control can affect the governor setting, the design values in the governing-load sharing control system affect the transient overspeeding.



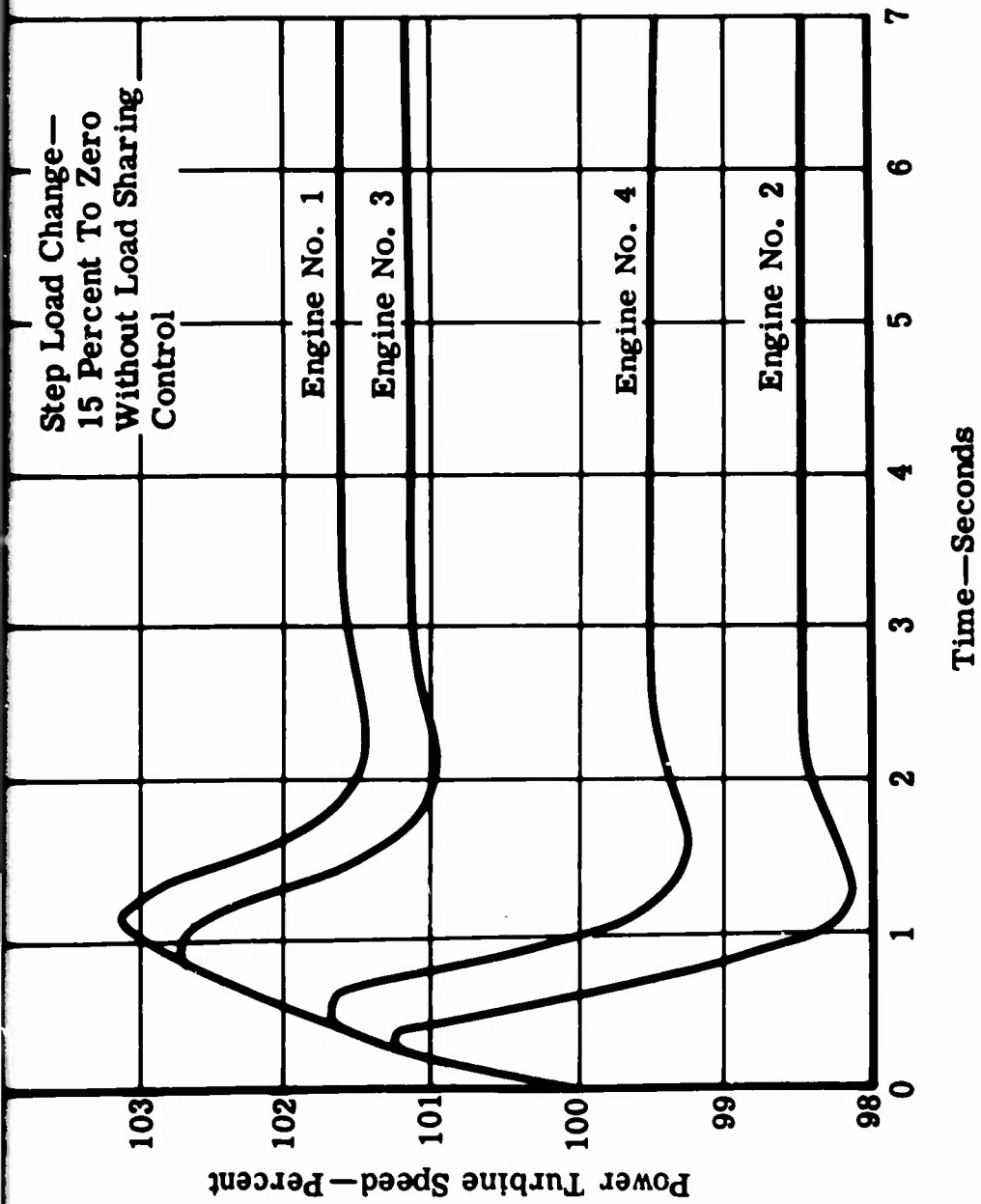


Figure 35. Decoupled Stability—Four Engines.

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TABLE XI					
TRANSIENT PERFORMANCE CHARACTERISTICS					
Engine—Control System Configurations				Percent Transient Rotor Speed Change With a One-Second Load Torque Change	
				100 To 23 Percent	23 To 100 Percent
Engine Systems Identical	Excluding All Governor Effects		A	2.3	-8.0
	With Governor	$\tau_r=0.5$	B	3.8	
		$\tau_r=0.1$	C	2.4	
With engine system differences	With load sharing control	$\tau_Q=0.05$ $\tau_r=0.5$	D	4.5	
		$\tau_Q=2.0$ $\tau_r=0.5$	E	4.0	
		$\tau_Q=0.05$ $\tau_r=0.10$	F	3.2	
		$\tau_Q=2.0$ $\tau_r=0.1$	G	2.8	

Where:

τ_r = Lagged Gain Reset Time Constant of Power Turbine Governor

τ_Q = Load Sharing Control Lag Time Constant

Configuration A in Table XI defines the ultimate capability of the engine and rotor system as limiting the transient rotor overspeed to 2.3 percent. This is based on the fuel flow being regulated by the deceleration fuel limit schedule during the major portion of the transient, with the governor(s) and load sharing control not affecting the deceleration rates. All engines and control systems are identical in their scheduling and dynamic performance.

Configurations B and C in Table XI include the effects of the power turbine governor, indicating a peak rotor overspeed of 3.8 and 2.4 percent for power turbine governor lag reset gain time constants of 0.5 and 0.1 second, respectively. This is the range of time constants determined by the nonlinear stability analysis to be satisfactory with regard to torsional excitations and low frequency governing stability. These configurations have identical engines and control systems.

Configurations D, E, F, and G in Table XI include engine control system differences with the load sharing control operative, illustrating the effects of governor and/or load sharing control dynamics. As indicated by these data, the peak transient rotor speed can be reduced with the low governor lag and high load sharing control lag (Configuration G). However, associated with the high load sharing control lag time constant is a larger torque difference between engines, which persists for several seconds. This is because a load sharing control lag of 2 seconds effectively prevents the load sharing control from functioning during the transient.

A more desirable compromise would be Configuration F, which has a low governor reset lag and a low load sharing control lag. This would result in a transient overspeed peak of 3.2 percent, with close torque balancing during the transient.

Transients Without Load Sharing

Figure 33 illustrates the resulting computer simulation transient performance for a four-engine system with the closed-loop load sharing control not operating (Configuration C). These data indicate the magnitude of the torque difference between engines that could occur. Except for the large torque differences, the transient performance and stabilization are shown to be quite satisfactory. Because of the large load sharing unbalance in the transient caused by a net load change from 100 to 23 percent (in 1 second), the Number 1 engine momentarily decoupled (zero torque) and then recoupled to become a part of the power generating system when stabilized. The small steady-state rotor speed change with power level, which is indicated, is due to an imperfect lever coordination schedule.

Transients With Load Sharing Control

Figure 36 defines the performance of a four-engine system with the load sharing control operating, illustrating the improvement in engine power balancing that could be obtained over the operation without the control (Figure 33). The width of the torque line represents the maximum torque difference between the engines. Transients A and C are for load changes in 1 second, while B and D define the performance for load changes in 3 seconds. The resulting transient response and stabilization characteristics are quite satisfactory.

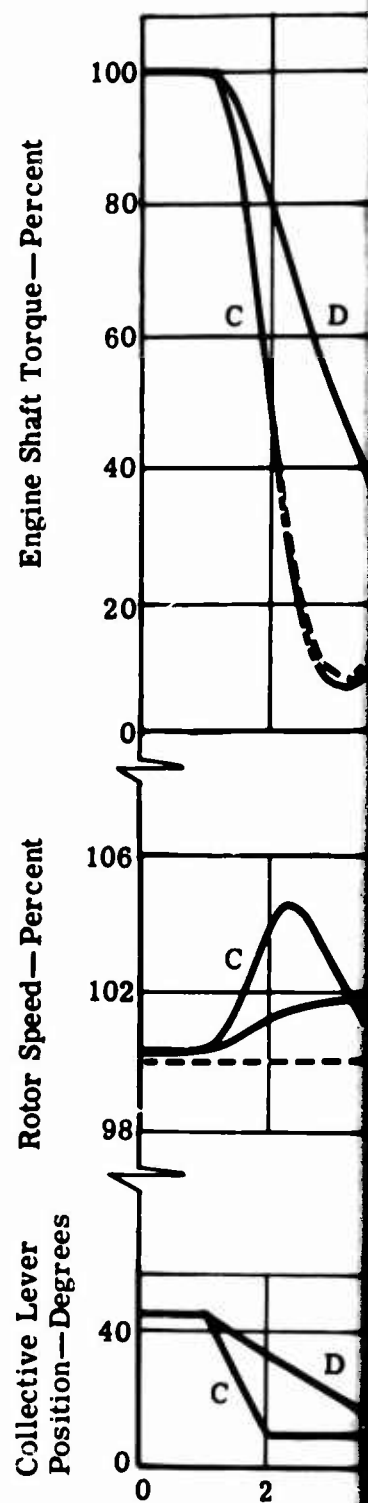
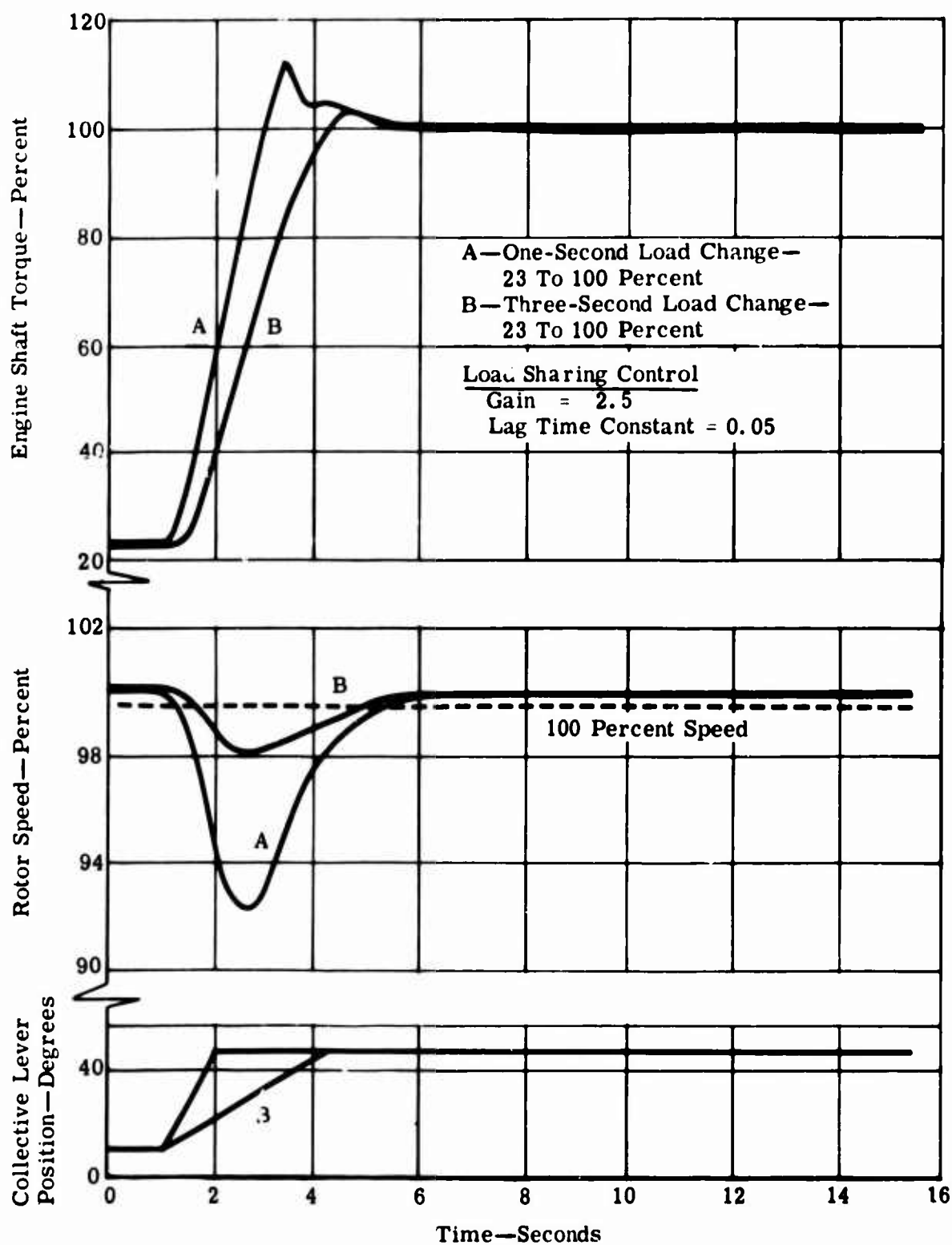
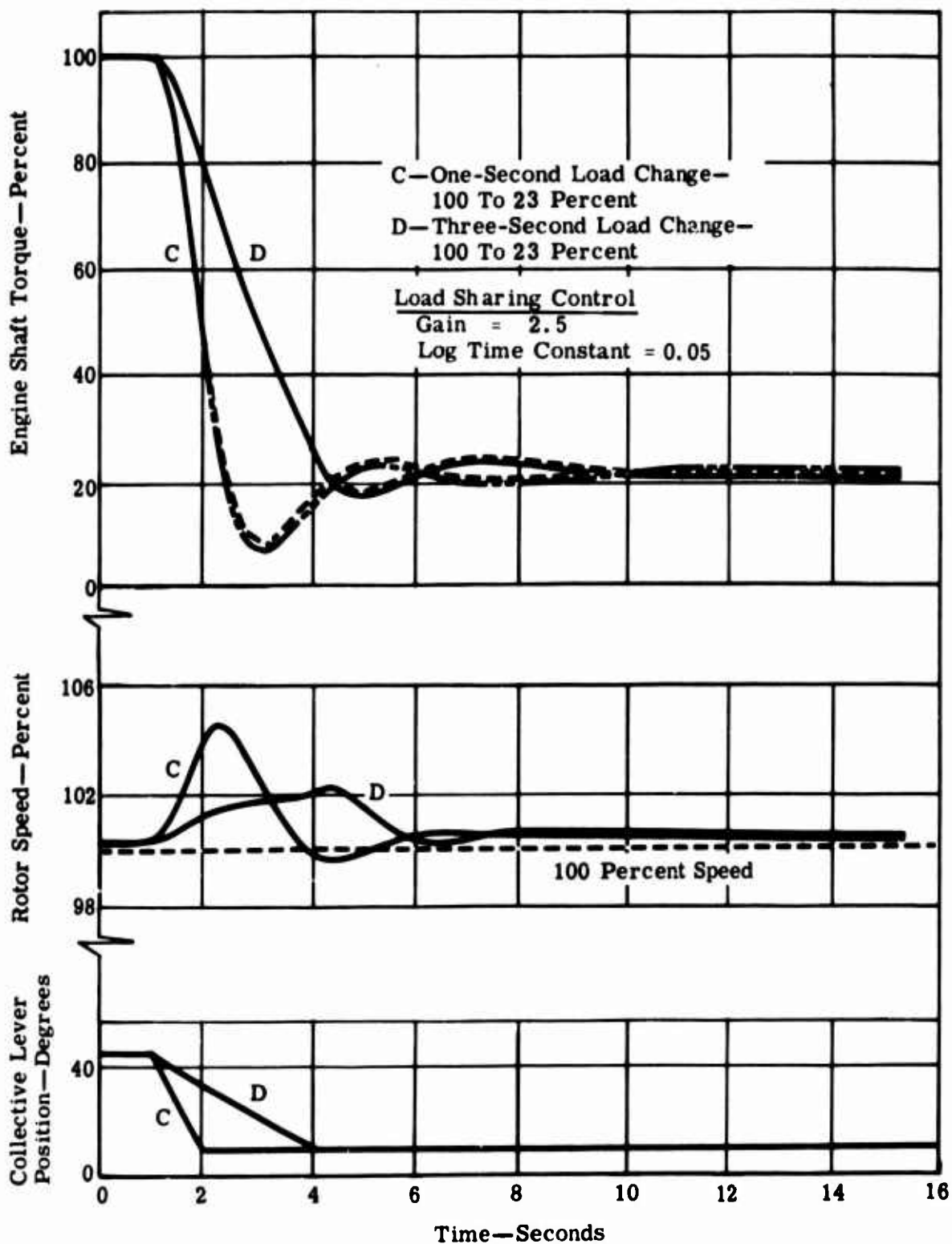


Figure 36. Effect of Load Change Rate on Transient Performance With Load Sharing—Four Engines.

A



With

B

Effect Of Two-, Three-, or Four-Engine System

The transient performance evaluation indicated that there is no discernible difference in the performance of a two-, three-, or four-engine system when the same control design and appropriate helicopter rotor system are used.

Effect Of Load Sharing Control Gain

Figure 37 illustrates the effect of load sharing control gain on the system performance with load changes. These data cover the range of load sharing control gains (ΔN_2 trim/ ΔQ error equals 1.0 to 2.5 percent per percent) that were determined to be desirable. The transient performance with the different control gains is quite satisfactory and nearly identical, except for the somewhat larger torque difference that occurs with the low gain control.

Effect Of Load Sharing Control Dynamics

There is no significant effect of load sharing control dynamics on the transient performance with rapid load increase. This is true even for the cases where one engine is a slow accelerator or a low power engine. This is primarily due to the fact that the significant portion of the transient is limited by the gas producer control acceleration schedule (because of the rotor underspeeding and collective-power turbine lever coordination), and not by the power turbine governor. The load sharing action, therefore, does not affect the engine operation until the gas producer acceleration has been essentially completed. The load sharing control dynamics can affect the time to stabilize at the steady-state torque balance, but control lags (time constants) of 0.05 to 2.0 seconds were investigated and determined to be satisfactory.

Load sharing control dynamics affect the transient performance with rapid load reductions, especially if the open-loop torque unbalance of the system is large and/or an engine is a slow decelerator. Figure 38 defines the effects of load sharing control lag time constant on the maximum torque difference and rotor speed during the transient. By increasing the lag to 2.0 seconds (or greater), the effect of the load sharing control action on the peak transient rotor speed is eliminated. Associated with the long lag time constant is a larger torque difference during the transient and a longer time to reach the steady-state torque balance condition. The longer time constant may not be warranted, considering the small improvement in the peak transient rotor overspeed that results, and the longer torque stabilization time.

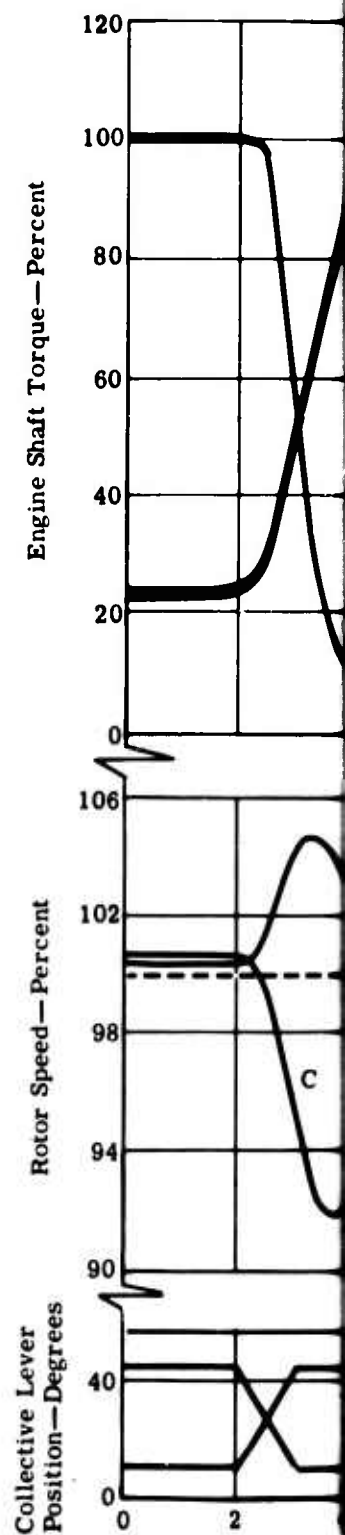
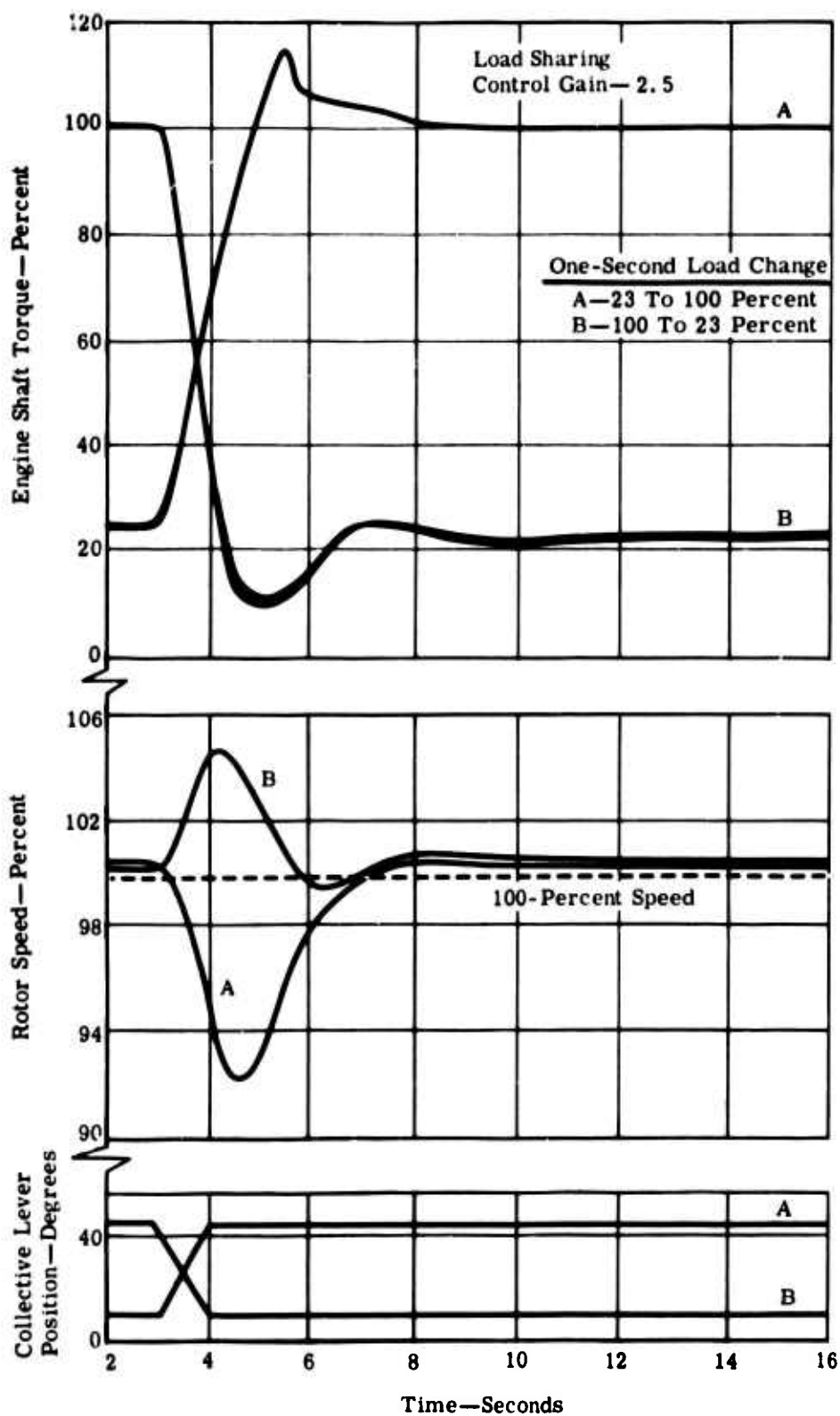
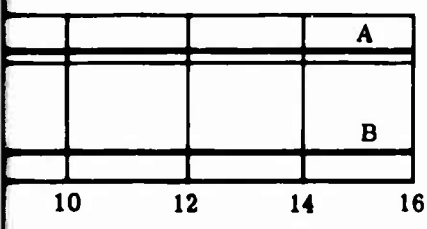
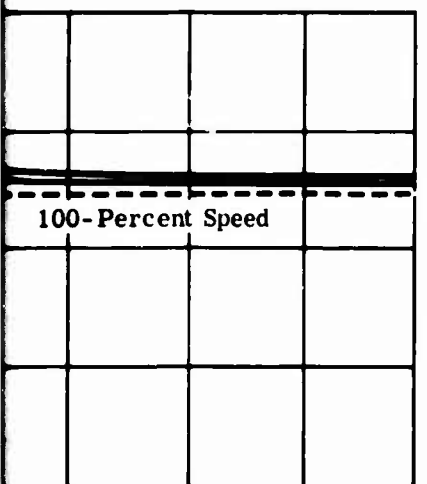
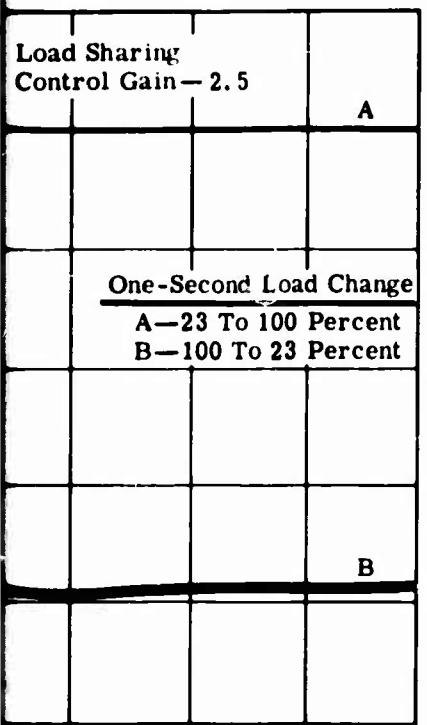
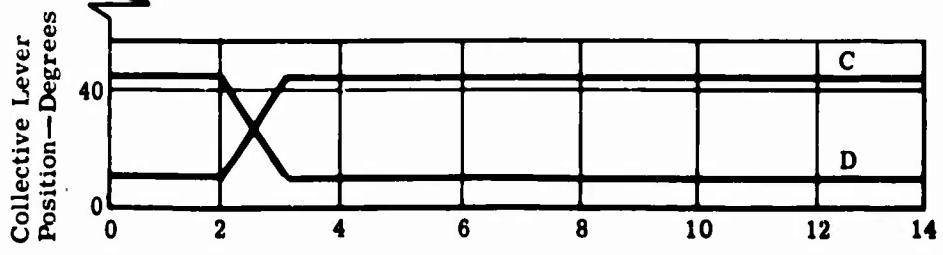
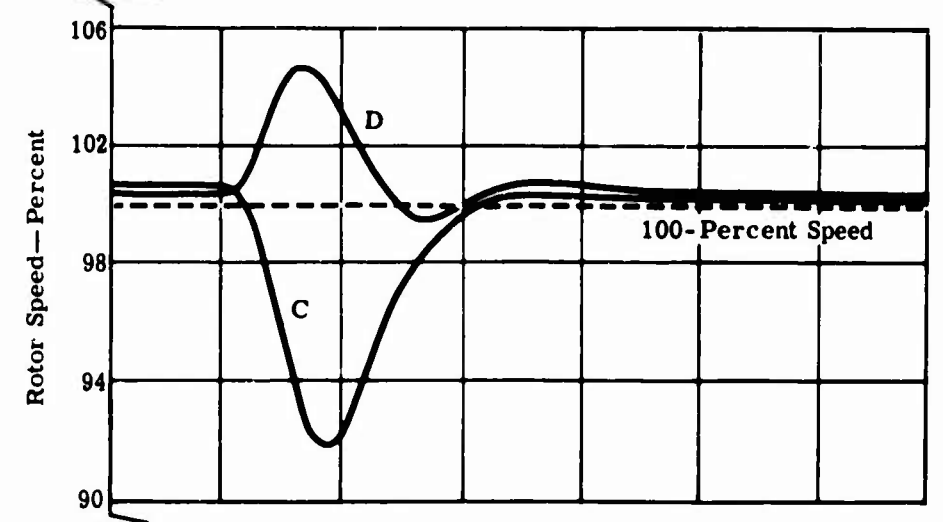
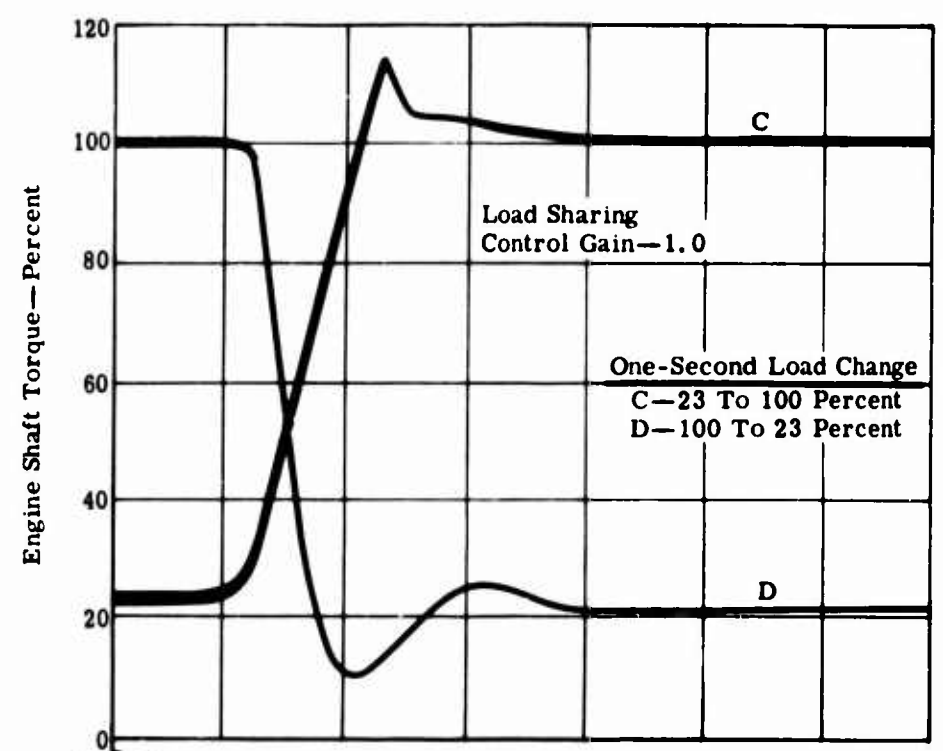


Figure 37. Effect of Load Sharing Control Gain on Transient Performance—Four Engines.



Seconds



Time—Seconds

Load Sharing Control Gain on Transient
—Four Engines.

B

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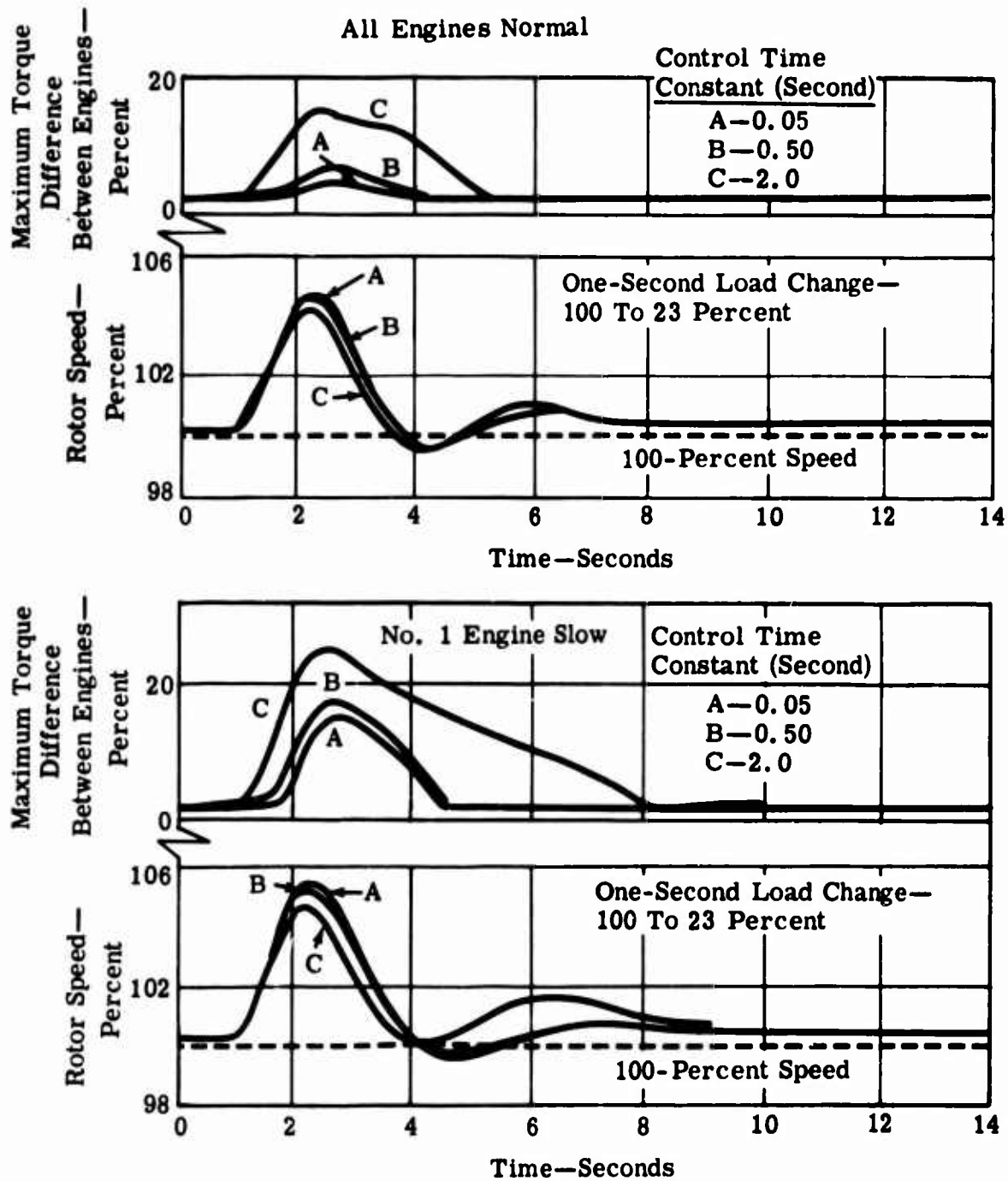


Figure 38. Effect of Load Sharing Control Time Constant On Transient Performance.

Effect Of A Slow Accelerating Engine

Figure 39 defines the four-engine and two-engine system performance with collective lever load changes, with one engine being slow on acceleration and deceleration. On the rapid load increase (run A), the three normal engines accelerated together, with no discernible difference in torques. The slower responding engine lagged during the power transient, reaching maximum torque and stabilizing at a later time. The slower accelerating engine had acceleration rates equal to 66 percent of those of normal engines. Since the load sharing control, by design, cannot lower the governor settings of the high torque engines, transient torque difference will occur. This results in the maximum transient response from all engines. Neither the power turbine governor nor the load sharing control affected this transient characteristic. Instead, the engines were limited by their acceleration fuel schedules (and maximum gas producer governors).

Figure 39 indicates a larger torque difference between engines during a deceleration transient (run B) than with all normal responding engines (Figure 37), with a larger transient rotor speed peak. The slower decelerating engine had a deceleration rate equal to 50 percent of normal engines. The larger torque difference occurs because the load sharing control action is limited in its governor trim authority and cannot completely slow down the normal engines to match the slower decelerating engines. The effect of the load sharing control on engine response is small, causing a 0.8-percent increase in the peak transient rotor speed. As previously mentioned, this effect would be eliminated with a lag time constant of 2.0 seconds. This would result in the maximum deceleration transient response from all engines, but would cause an even larger torque difference during the transient and a longer time to reach the steady-state torque balance condition. The longer lag may not be warranted because of the small transient performance improvement that it affords.

Effect Of One Engine Shut Down

The transient response of four- and two-engine helicopter systems with one engine shut down was investigated. The system performance was satisfactory, with the obvious limitations due to the reduction in the maximum available power. The result is that maximum allowable helicopter loading (collective lever) is less than it is with the engine operating, with the two-engine system being more adversely affected than the four-engine system. This is because the power reduction is a larger percent of the total design power. The rate of change of collective lever, however, must be reduced, or larger transient rotor speed excursion will occur.

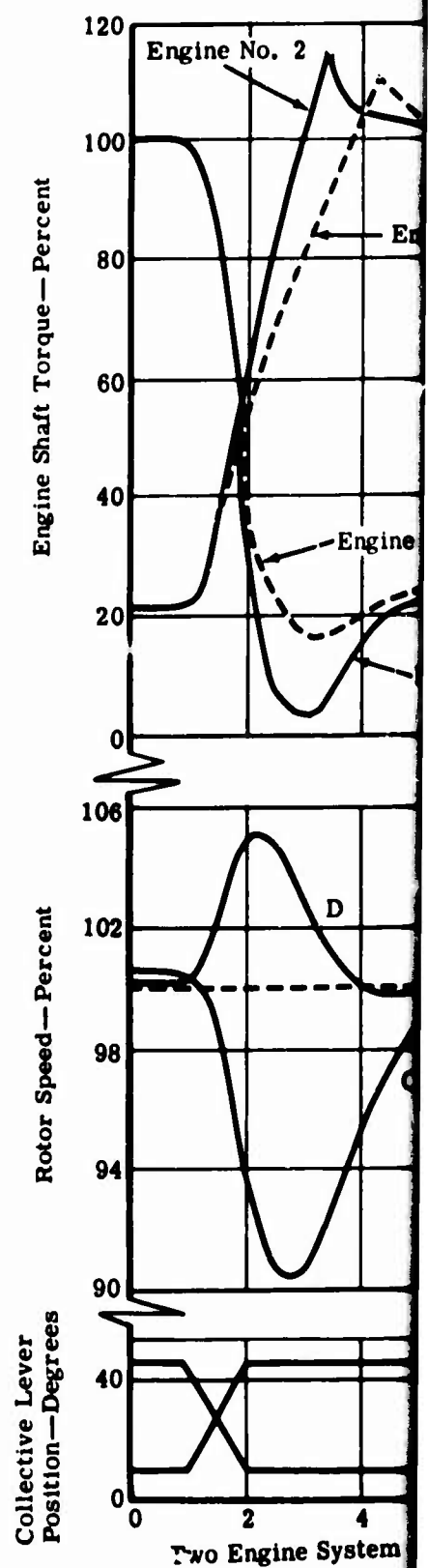
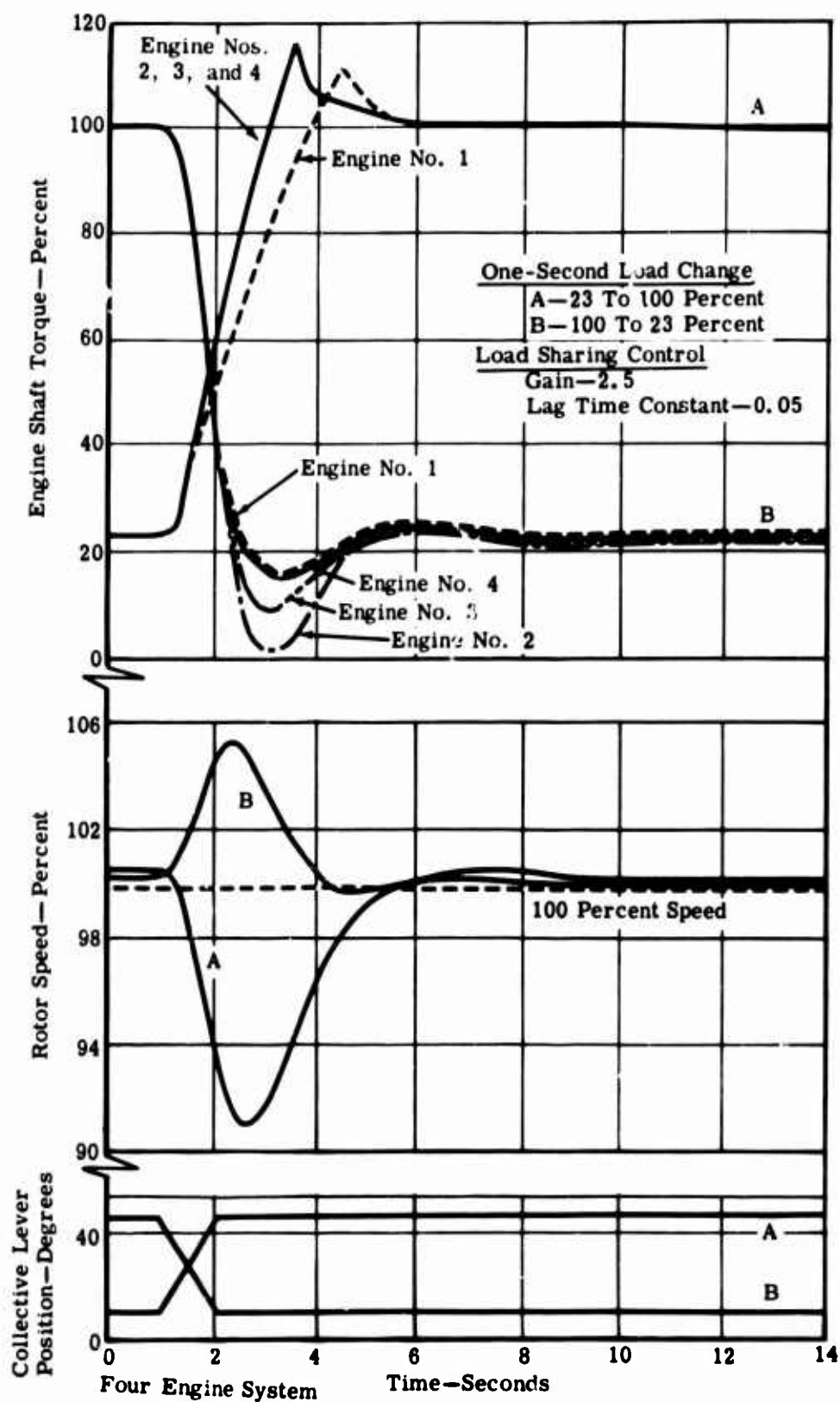
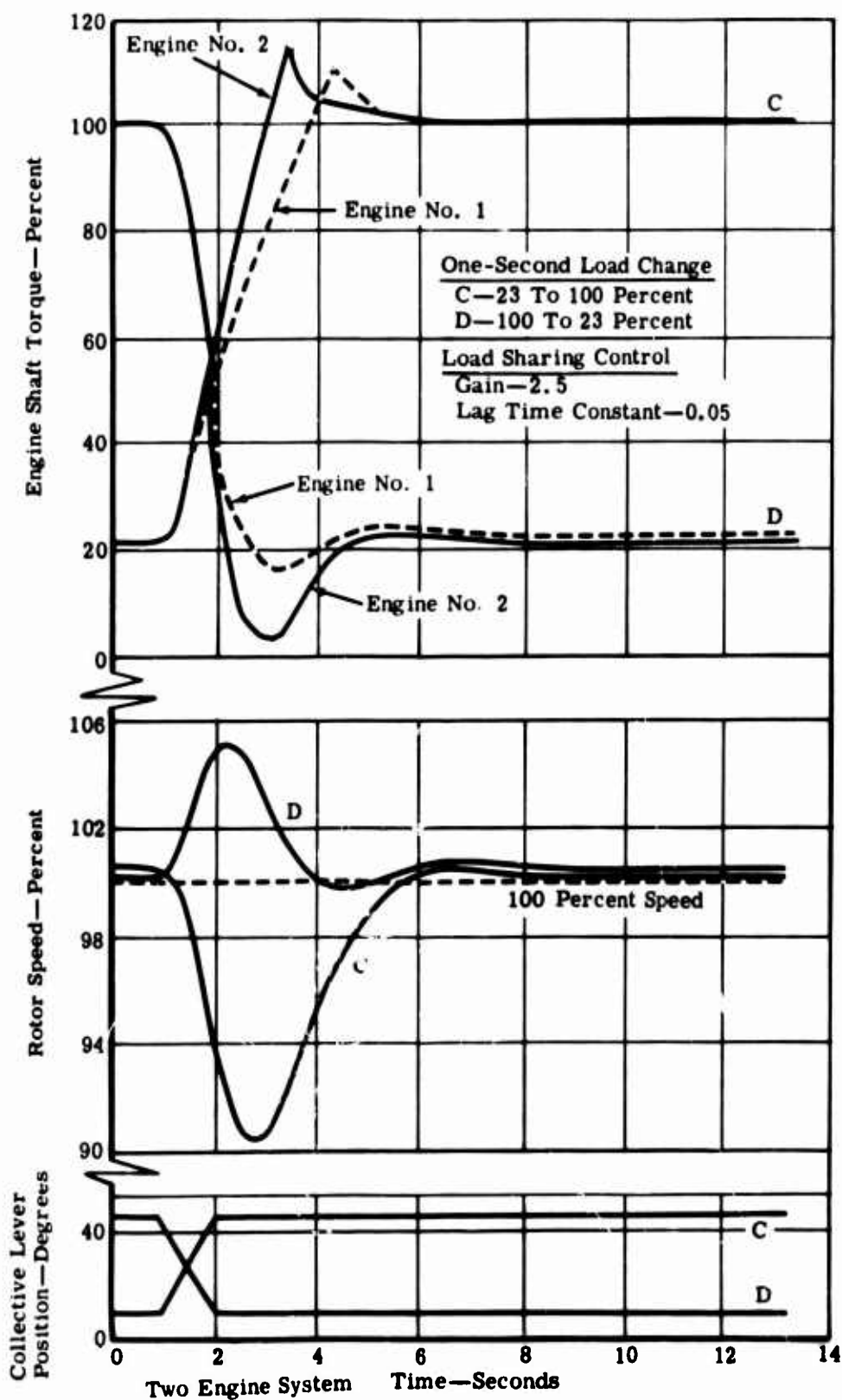
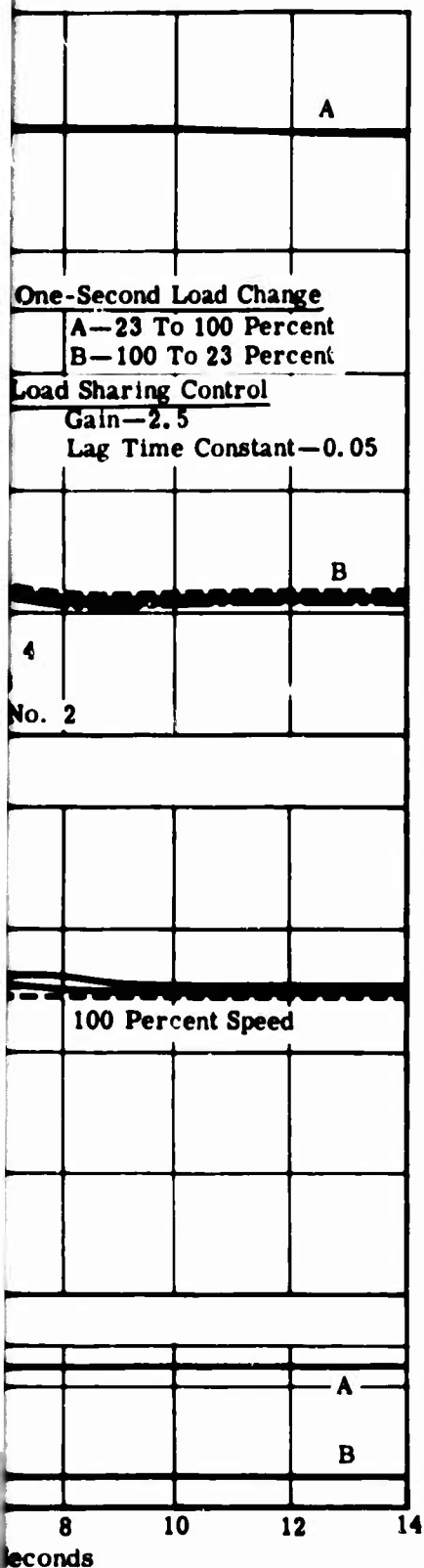


Figure 39. Load Sharing Transient Performance—Slow Engine.

A



Transient Performance—Slow Engine.

B

SINGLE GOVERNOR WITH OPEN-LOOP LOAD SHARING

The single-governor concept was investigated as a possible means of obtaining satisfactory load sharing without employing a closed-loop load sharing control. This could result in a system that would provide the desired performance characteristics with a system of minimum complexity and in-service maintenance.

The evaluation of this concept has resulted in the conclusion that this concept will not result in a multiengine control system simpler than the individual governor-closed-loop load sharing control concept. This is because of the necessity for employing additional control functions to correct certain characteristic deficiencies of the single-governor concept. The load sharing accuracy, therefore, would not be as good.

Multiengine Performance

The major contributors to the power unbalancing were determined to be in the power turbine governor, i. e., the governor speed set point and the gain. In the single governor concept, one power turbine governor would be used to operate all gas producer controls equally and simultaneously. This would result in open-loop load sharing accuracy improvement to an acceptable level. As previously shown, the steady-state load sharing accuracy analysis indicated that the maximum power difference of the single governor concept would be 11.5 percent compared to 38 percent for individual governors without a load sharing control and 2 percent for individual governors with a load sharing control.

The single-governor system was included in the multiengine power system evaluation to allow investigation of its dynamic performance. Figure 40 illustrates the control system differences that were employed. The Number 1 engine was selected to provide the governor signal.

Collective lever transient runs were made, with the conclusion that on the 23 to 100 percent and 100 to 23 percent load transients, this system performed satisfactorily. The resulting transient data were very similar to an individual governor-closed-loop load sharing control system with a very low gain load sharing control ($\Delta N_2 \text{ Trim} / \Delta Q \text{ Error} < 0.2$).

Decoupled Operation

Transients were also run from high power levels into the zero horsepower (autorotation) condition. These transients indicated a shortcoming of this

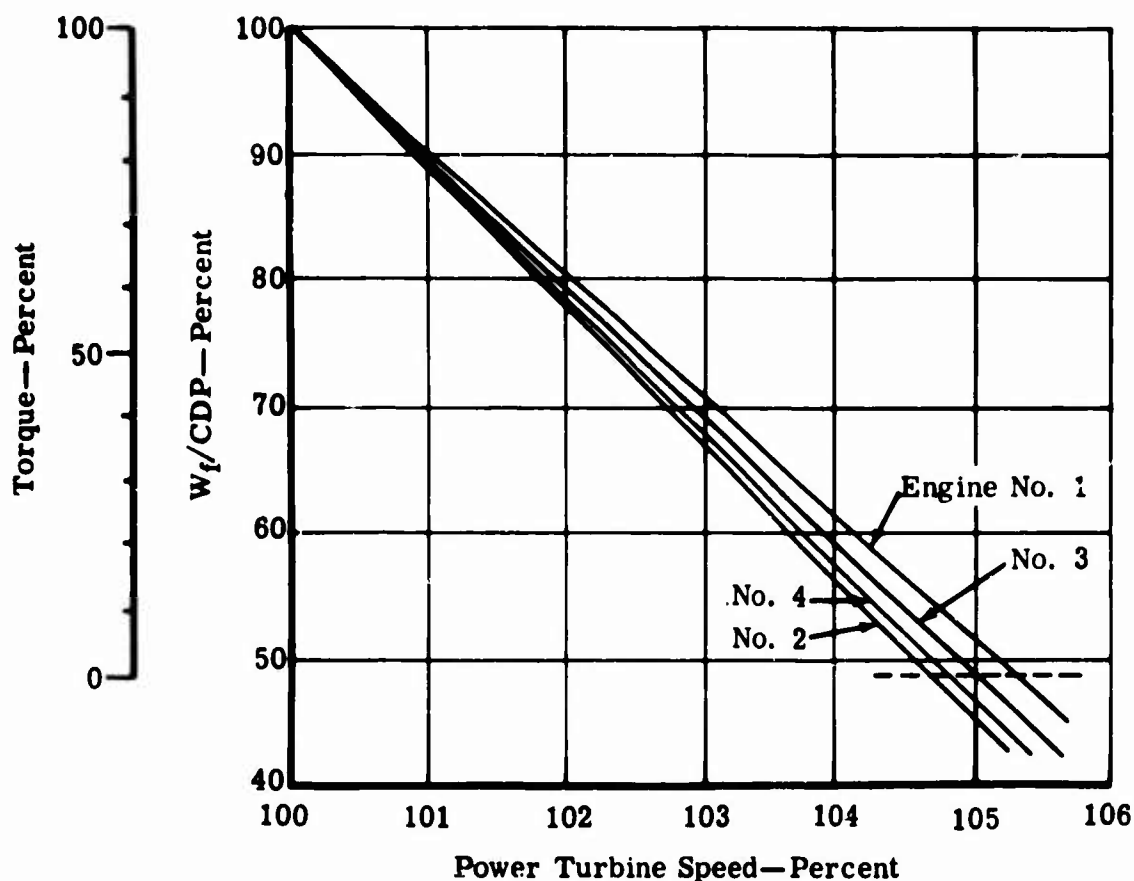


Figure 40. Assumed Control Characteristics With A Single Governor.

concept because the different engines do not reach zero power at the same turbine speed. The problem is associated with engines decoupling at different load conditions because of unequal load sharing and operating at a different power turbine speed. The result of this would be either an inability to obtain a normal power reduction when necessary or engines operating at conditions from which they may not be able to recover upon demand (or possibly gas producer bogdown).

As was previously explained, the single governor concept utilizes one governor to reset the individual gas producer controls equally and simultaneously. This eliminates the effect of power turbine governor production variations and collective reset errors on load sharing. However, there would still be some unbalance with this open-loop load sharing concept because of the variations among the individual gas producer controls in metering fuel in response to the power turbine governor signal. An explanation of this effect is presented in the following paragraphs for a two-engine configuration to simplify the presentation; however, it is also true for three- and four-engine configurations.

The inability to obtain a normal power reduction to zero would occur when the single power turbine governor is driven by the engine which has a lean gas producer control (Figure 41). In this case, the lean engine would reach zero power, decouple, and stabilize at constant power turbine speed (point A). The rich engine would be producing over 10 percent power (point B) at the time the governing engine decoupled and would receive no further signal change to effect the required reduction in fuel flow to obtain zero power. Instead, the rich engine would not reach zero power until a turbine (and helicopter rotor) speed of over 110 percent was reached (point C).

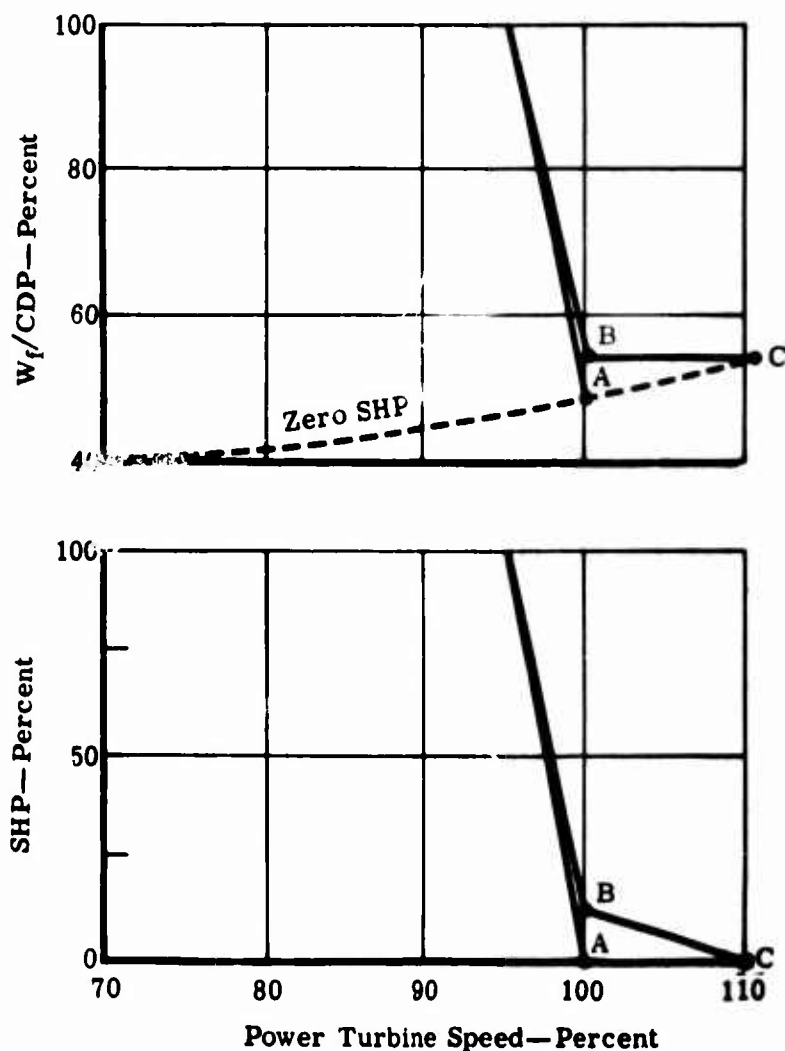


Figure 41. Single Governor on Lean Engine.

The potential of driving a gas producer rotor to a low speed from which recovery may not be possible would occur if the single power turbine governor was driven by the engine which employed the rich gas producer control (Figure 42). Because of the rich control, this engine would require more trim action by the governor (more power turbine speed change) to reach zero power (point A) than is required for the lean engine (point B). This governor action would then cause the lean engine to receive a lower-than-necessary fuel flow, resulting in a very low gas producer speed and a reduced power turbine speed (point C). Depending on the specific magnitudes of the control differences and the characteristics of an engine, this could result in the lean engine being operated at a fuel flow (or gas producer speed) so low as to prohibit power recovery on demand.

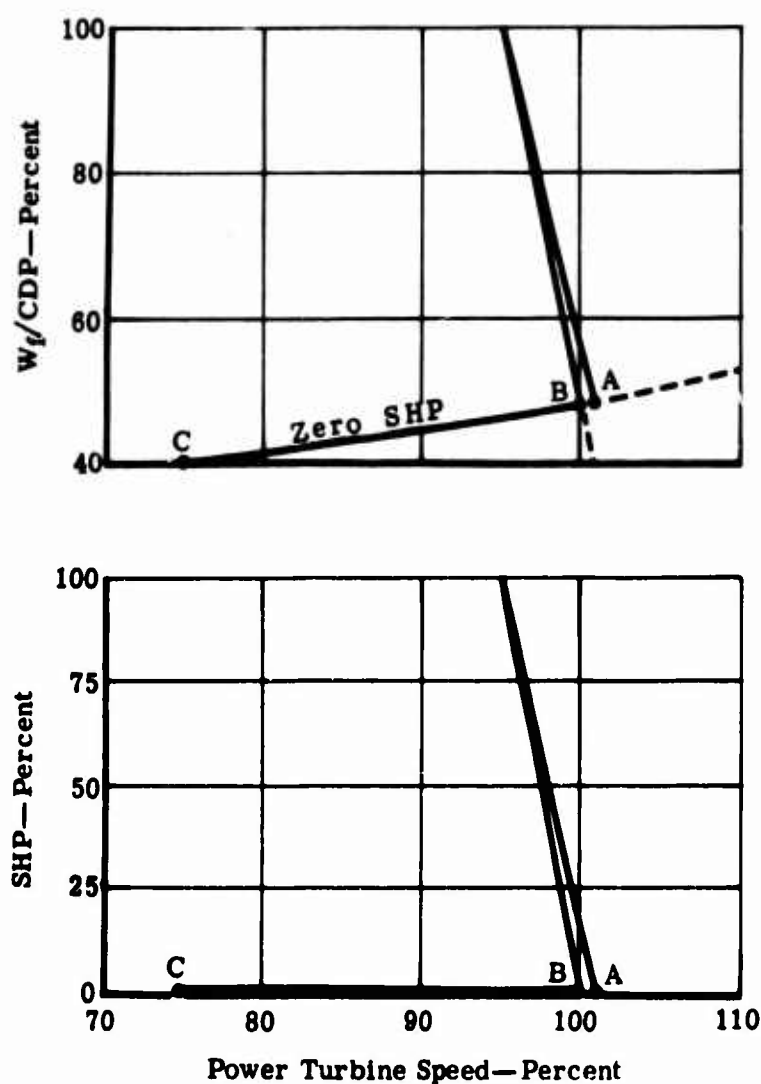


Figure 42. Single Governor On Rich Engine.

Several possible solutions for alleviating this zero power problem were evaluated. One was to rig the controls in the aircraft so that the engines would be perfectly matched at the low power condition, thereby achieving simultaneous decoupling of all engines. This would result in an unequal load sharing at high powers, with a power difference between engines of up to 12 percent. This power unbalance at high power would not be acceptable and thus is not an acceptable solution.

Another approach investigated was to provide a gas producer underspeed governor function in each fuel control to prevent the power turbine governor from driving any engine speed too low. This approach is fundamentally satisfactory, but an additional function in the gas producer control would be required. This approach will not provide protection when the controlling governor is on the lean engine.

Another approach considered would involve mounting the power turbine governor on the helicopter transmission downstream of the overrunning clutches. Along with this, gas producer underspeed governors would also be required. This would then prevent the necessity for high helicopter rotor speeds to achieve zero net power (lean engine system), and prevent bogdown of gas producers (rich engine system or with helicopter rotor overspeed in autorotation). This system would then function satisfactorily for all normal conditions.

Failure Considerations

The overall system reliability, as related to the multiengine helicopter operation, would be greatly compromised by employing a single transmission mounted governor. A normal advantage of a multiengine helicopter, over a single engine design, is related to the ability to continue flight operation with a malfunction of a single engine (or control system). With a single transmission driven governor, the engine power control system would continue to function satisfactorily in the event of a malfunction of an engine or gas producer control. However, if the power turbine governor were to malfunction, the control of power on all engines would be lost. To obtain reliability similar to that of the individual governor concept, more than one transmission mounted power turbine governor must be employed. A special governor malfunction detection device would also be required to automatically change the controlling governor when necessary. The result would be a system as complex as, or more complex than, that of the concept of using individual governors with closed-loop load sharing.

AUTOMATIC POWER RECOVERY WITH AN ENGINE OUT

The gas turbine engines for the multiengine helicopter will provide an emergency power level that is higher than the normal maximum operating power level (military). The control system design will be such that the engine operation will be automatically limited to military power during normal operation. To obtain emergency power capability, the controls must be reset by a command signal.

One of the main reasons for providing an emergency power rating in the multiengine helicopter is to enable safe operation and recovery of the aircraft with a loss of power from one of the engines while in a critical flight mode. Because of the necessity for the pilot to devote his attention to flying the aircraft when in this mode, the lag associated with his detection of the occurrence of a malfunction and the determination and initiation of the corrective action required would be too great to enable safe recovery. This is especially true when considering systems of more than two engines or when considering a malfunction while the engines are undergoing power transients.

An automatic malfunction detector was investigated as a means for providing an early warning of the malfunction and initiating corrective action.

Malfunction Detector

Requirements

The basic requirements are that the system must detect and signal the occurrence of an engine malfunction. The time lapse between the occurrence of the malfunction and the generation of the signal must be small.

Some of the specific conditions for which proper functioning are required are as follows:

- In gross engine power transients
- At all power levels
- When turbine temperature is limited or gas producer speed is limited
- With any engine shut off or at ground idle
- With normal engine performance differences
- Throughout the normal range of ambient conditions

Parameter and Mode

The performance and operation analyses indicated that the detector should utilize the engine parameter gas producer speed, analyzing the speed differential between engines to determine the occurrence of a malfunction. If the differential between the highest and the lowest speed engines exceeds a predetermined value (possibly 5 percent), a malfunction would be signaled. This concept was selected because it would meet the defined requirements and was not complex.

The original functional design evaluation included combined gas producer speed differential and engine torque differential logic circuits. The torque circuit was included because it was recognized that it would provide an early indication of flameout at high power. Engine testing conducted at Allison on a free-turbine engine showed that after a flameout at a high power level, the torque signal will rapidly decrease 40 percent prior to any gas producer speed change. However, the results of dynamic studies of this design indicated that the torque signal mode and the gas producer speed mode reaction time differences are insignificant. This is because the initial gas producer deceleration rate is very high at flameout, with a 7 percent speed reduction occurring in less than 0.2 second. The effect of this small time delay in selecting Emergency power is insignificant in terms of transient speed droop of the helicopter rotor. Torque differential alone is a good indication of flameouts or other failures at high power but is not satisfactory in the very low power range (zero horsepower). The difference between a normal operating engine and a flameout (or gas producer bogdown) at low power would not be discernable. Also, the torque parameter is not good when considering altitude operation. Therefore, the added complexity of a torque-sensitive subcircuit is not warranted.

Design

Figure 43 is a schematic of an electronic malfunction detector design. An electronic design was selected as the optimum approach because of the necessity of sensing all gas producer speeds, the type of logic associated in the detector, the detection response desired, and the type of output signal required. This component receives gas producer speed signals from all engines, discriminates to select the highest as a reference, and then compares each speed signal to the reference. If any differential is greater than the predetermined safe value, the detector would indicate a failed condition.

This specific design approach was selected to facilitate operation with an engine(s) purposely shut down or operating at ground idle. Condition lever override signals are provided to deactivate portions of the computer in the event an engine is shut down by the pilot so that the malfunction signal is not generated.

Speed Differential Setting

The multiengine simulation was employed to evaluate the malfunction detector design, with and without the load sharing control in operation. The individual governor concept was utilized in the analysis to determine the speed differential setting required to prevent inadvertent operation of the detector during normal conditions. Table XII indicates the maximum gas producer speed differences (ΔN_1) that occurred.

TABLE XII		
MAXIMUM GAS PRODUCER SPEED DIFFERENCES.		
Engine Response	Load Sharing Control	Maximum N_1 (Percent)
All Normal	OFF	7.2
Number 1 Slow	OFF	8.4
All Normal	ON	2.8
Number 1 Slow	ON	4.8

The low engine in this simulation had gas producer rotor response rates one-half as fast as the normal engine. Table XII indicates that a 5-percent setting would be satisfactory with the load sharing control operating; with the load sharing control off, an 8.5-percent setting would be required. Since normal operation would be with the load sharing control functioning, it would not be desirable to compromise the malfunction detector for the other case (load sharing off). A speed differential setting of 5 percent would then be employed. The selection circuit design would be arranged so that the malfunction detector would be armed only when the load sharing control is in operation.

Power Recovery Capability

As previously indicated, the malfunction detector signal would be utilized to reset all gas producer controls to enable emergency power operation. This would then allow the power turbine governors of the operating engines to increase their power levels as required to compensate for the engine failure.

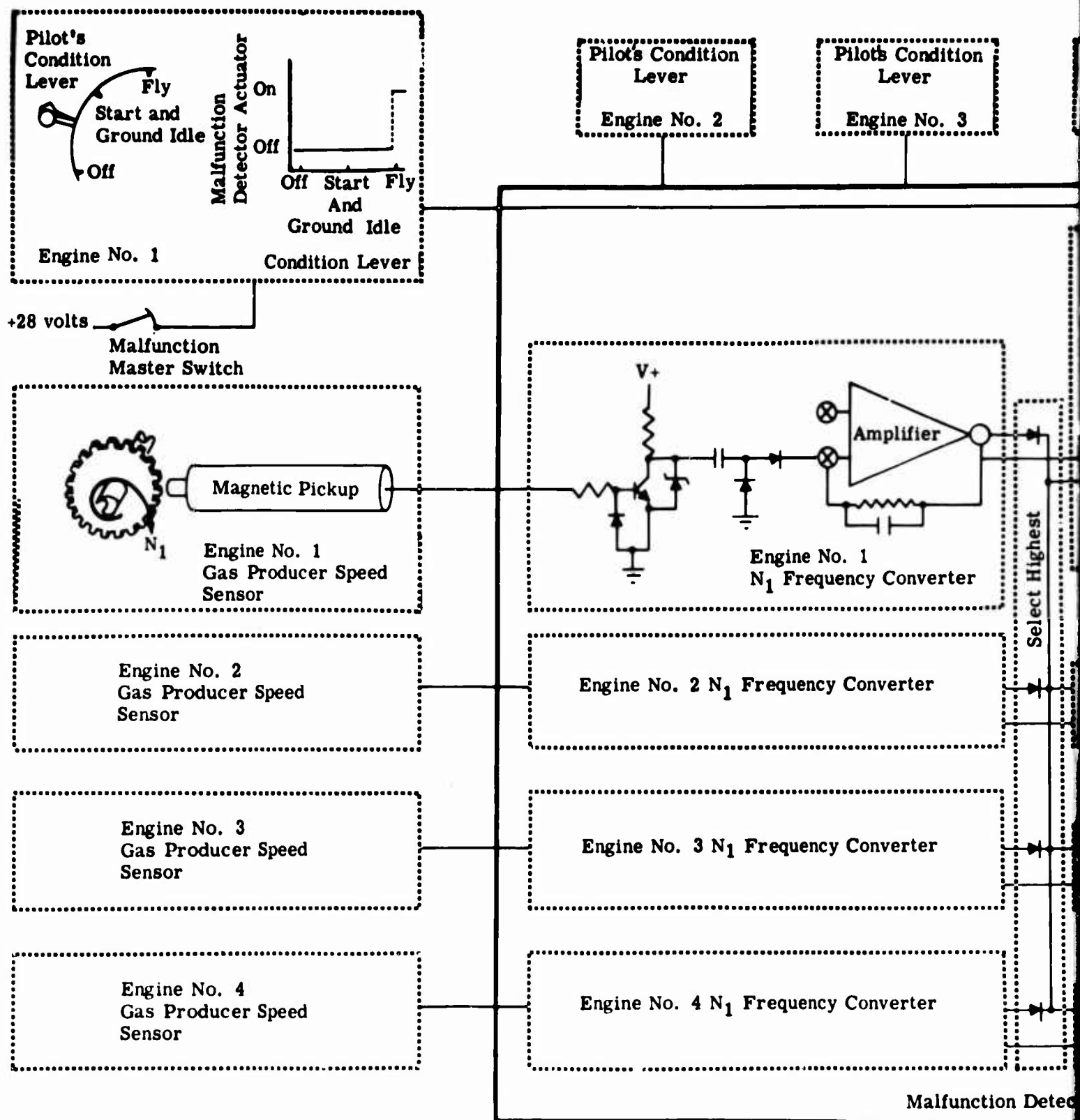
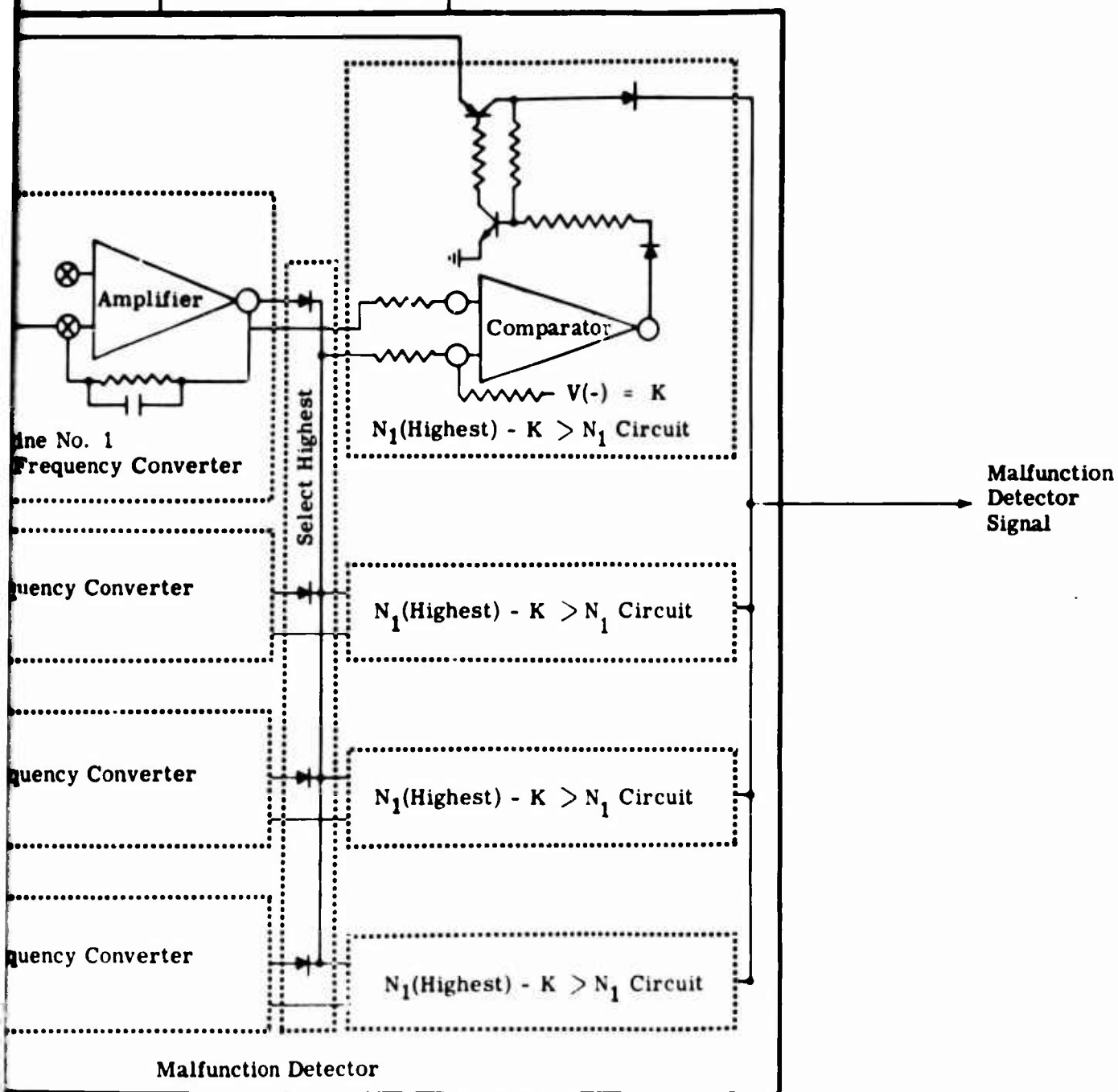


Figure 43. Schematic of An Electronic Malfunction Detector Design.

A

Pilots Condition
Lever
Engine No. 3

Pilots Condition
Lever
Engine No. 4



B

Analysis of the performance of this system during an engine failure indicated that a shift (reduction) in governed speed would occur. This is because the collective-power turbine lever coordination schedule is based on power being provided by all engines. The magnitude of the speed shift (ΔN_r) with an engine out is dependent upon the steady-state governor gain and the number of engines normally in the system. These data for a governor gain equivalent to 5 percent speed droop from zero to maximum power (at a constant power turbine governor lever position) are as follows:

<u>System Design</u>	<u>ΔN_r With Engine Out (Percent)</u>
4 engines	1.25
3 engines	1.67
2 engines	2.5

The speed shift is largest for the system design of two engines because the percentage of power change when an engine fails is largest.

The speed shift could be trimmed manually, with the pilot resetting the collective power turbine governor lever scheduling. An alternate approach would be to employ the malfunction detector signal to reset the power turbine governor(s) at the same time it resets the gas producer control. Figure 44 illustrates the performance of a four-engine system with and without the power turbine governor reset. The effect of the reset is illustrated as a reduction in transient speed droop and the elimination of the shift in governed speed. Because of the small transient performance improvement and the associated added complexity, resetting of the power turbine governors by the malfunction detector does not appear warranted. Manual trim of the governor setting, for this failure condition, should be satisfactory.

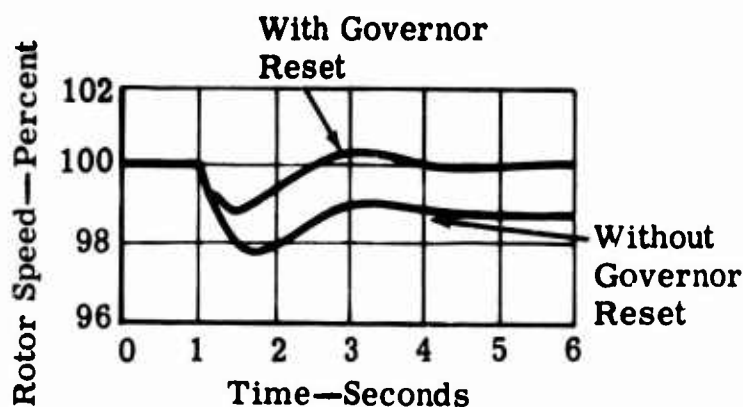


Figure 44. Effect of Malfunction Detector Reset of Power Turbine Governor With an Engine Failure.

CONSTANT SPEED CONTROL

Two methods of providing constant rotor speed operation of the multi-engine helicopter were evaluated; i. e., collective-power turbine lever coordination and isochronous governing. The collective-coordinated concept is the conventional one where the power turbine governor lever is varied as a function of the collective lever position to prevent the speed change due to load change normally associated with the proportional governor. The isochronous governor utilizes the sensed speed error signal to trim the proportional governor, providing a proportional-plus-integral characteristic.

The collective-coordinated method is recognized as not being precise, but as being an open-loop approach. In the multiengine system, the mechanisms required to provide the coordination may also be complex. For these reasons, the evaluation of the isochronous design was conducted.

The collective-coordinated method should provide satisfactory steady-state speed control; and it is considered to be desirable with regard to collective lever transients. Some manual trimming may be required.

The isochronous (integrating) governor would result in poor transient response to load changes.

The integrating governor could be employed along with collective lever coordination of the proportional governors, but would not appear warranted when considering the added design complexity.

Collective Coordinated

A specific collective lever position does not require a specific power at all operating conditions, because the power required varies with the ambient and with the vertical and horizontal velocities. The power required is also affected by the cyclic action and the tail rotor. A speed governing accuracy study indicated that the rotor speed variation during a typical operation could be as large as 2 percent with this approach. As a result, occasional manual trimming (beeping) of the governor settings would be required of the pilot.

In the multiengine system, the coordination scheduling, if based on all engines operating, would not be correct with an engine off. If this type of operation is to be conventional, it must receive special attention in the design of the coordination schedule to minimize the required manual trimming by the pilot.

A desirable characteristic provided by collective coordination is the lead or anticipation signal to the power turbine governor on collective changes. This in effect, initiates an engine power change (fuel flow change) at the same time that the load change is being made, minimizing the transient rotor speed excursions.

Isochronous Governor

The isochronous governor investigated was an integrating type employed in conjunction with the proportional power turbine governor, resetting the speed reference to trim the speed error steady state. The proportional governor mode is the fuel flow/compressor discharge pressure with lagged gain reset. With the individual governor concept, all engines cannot employ isochronous governors, because of the inherent inability of isochronous governors to share the load in a power system that is mechanically coupled. This is because all governors would not be identical in the speed sensing and speed reference settings. The result would be instability due to the tendency of the governors to effect a full range power change for a very slight speed error.

An isochronous design was evaluated where one integrating governor was employed to trim all proportional governors equally and simultaneously. Figure 45 presents the stabilizing characteristics in response to step load change at high power and at low power, indicating the effect of the integrator gain. These data indicate that an integrator gain ($\Delta N_2 \text{ set} / \Delta t / \Delta N_2$ error, percent/second/percent) of between 0.5 and 1.0 would be required.

Performance Comparison

Figure 46 is a comparison of the transient characteristics of the collective coordinated and the isochronous systems for a 1-second load increase and decrease. These data indicate that the isochronous design is less responsive than the collective-coordinated design because of the lack of a lead signal. The result is a much larger transient rotor speed overshoot and a longer stabilization time following a rapid reduction of rotor collective pitch, when compared with the collective coordinated concept. It is anticipated that the rotor system would not be able to tolerate this type of over-speeding.

The data presented are for an isochronous governor with a 1.0 percent/second/percent integrator gain. The transient rotor speed excursions and stabilization times would be even larger with a 0.5 gain.

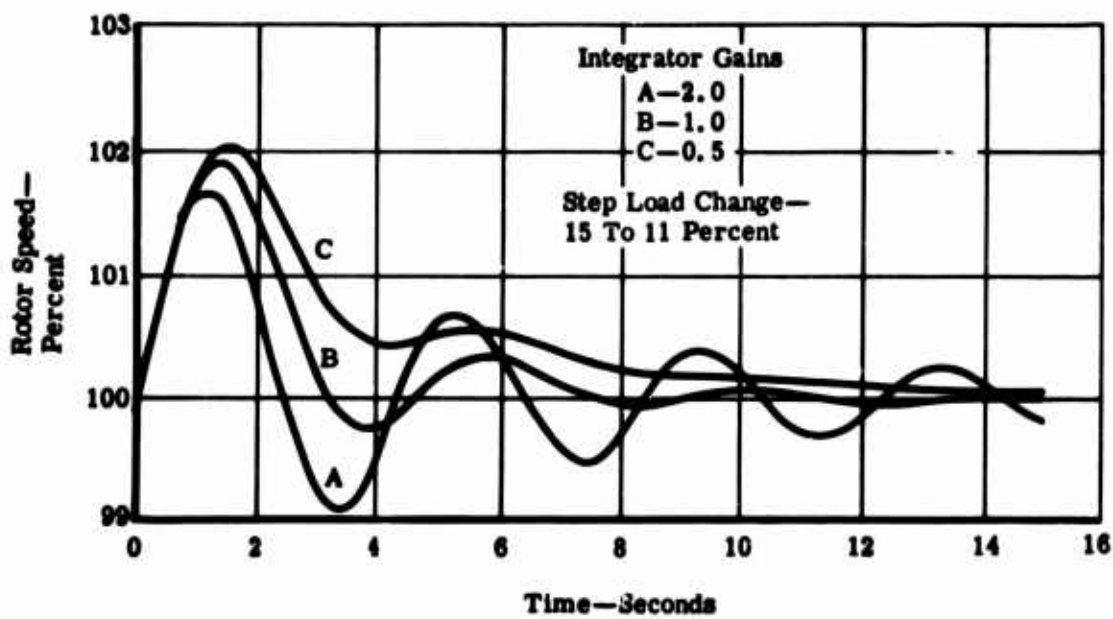
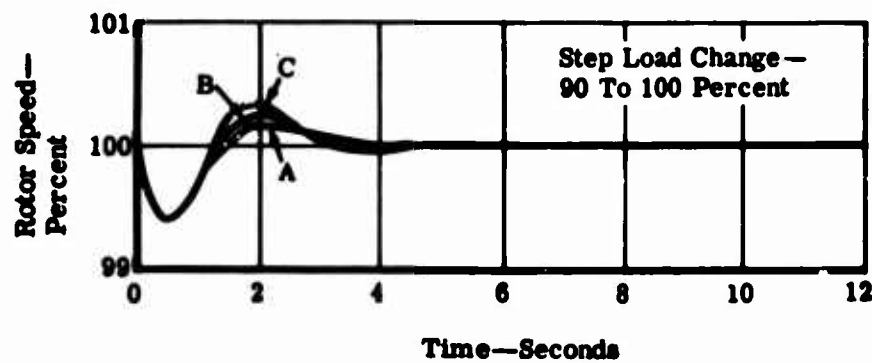


Figure 45. Isochronous Stability—With Load Sharing.

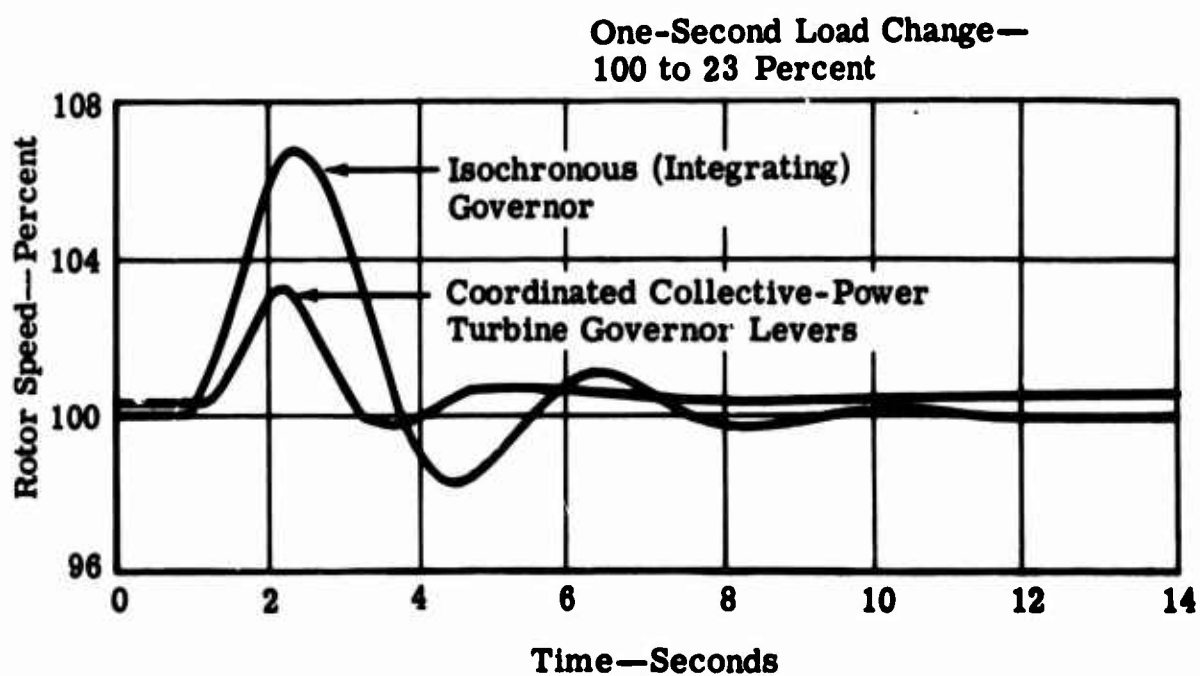
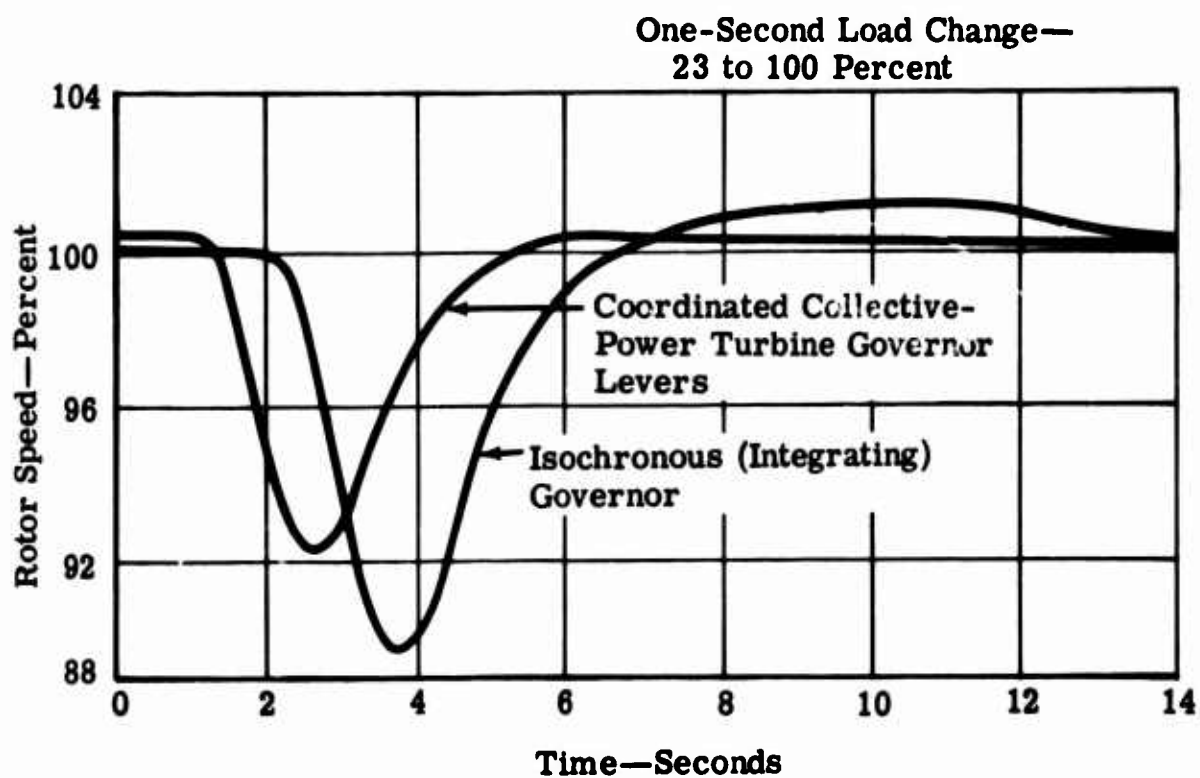


Figure 46. Transient Response Comparison of the Isochronous Governor With the Collective Coordinated Design.

An alternative would be to employ both the collective-coordinated concept and the isochronous governor. This would provide the maximum in transient response plus zero error when governing. This added complexity does not appear to be warranted, considering the small steady-state speed variation involved with the coordinated system and the ability of the pilot to correct this by manual trim.

GENERATION OF A POWER SYSTEM

A multiengine power system simulation was made for use in the analysis of control system dynamic performance. This was a nonlinearized representation of the engine, helicopter rotor system, and controls. A digital computer program was utilized to simulate the power system model.

The following paragraphs describe the simulation model and the computer program that was developed.

ENGINE

The Allison Model 501-M34 free turbine engine was simulated. It has a rated power of 5270 shaft horsepower. The engine develops rated power at 100 percent gas producer speed and zero power at approximately 80 percent gas producer speed when the power turbine speed is 100 percent.

The transient capabilities of the engine are 3 seconds to accelerate from zero to rated power and 2 seconds to decelerate from rated to zero power.

The engine was represented in the simulation in terms of nonlinearized maps that define the gas producer and the power turbine performance. The maps employed were as follows:

- Gas producer rotor acceleration rate as a function of fuel flow and gas producer speed
- Shaft horsepower as a function of fuel flow, gas producer speed, and power turbine speed
- Compressor discharge pressure as a function of fuel flow and gas producer speed

ROTOR SYSTEM

The helicopter rotor system simulated was based on information obtained from helicopter companies (Sikorsky Aircraft, Lockheed Aircraft, and Boeing Vertol). Figure 47 illustrates the configuration.

For configurations involving less than four engines, only the appropriate power turbines and torque meters were employed. The helicopter transmission, mast shaft, and rotor were scaled according to the number of engines in the design being evaluated.

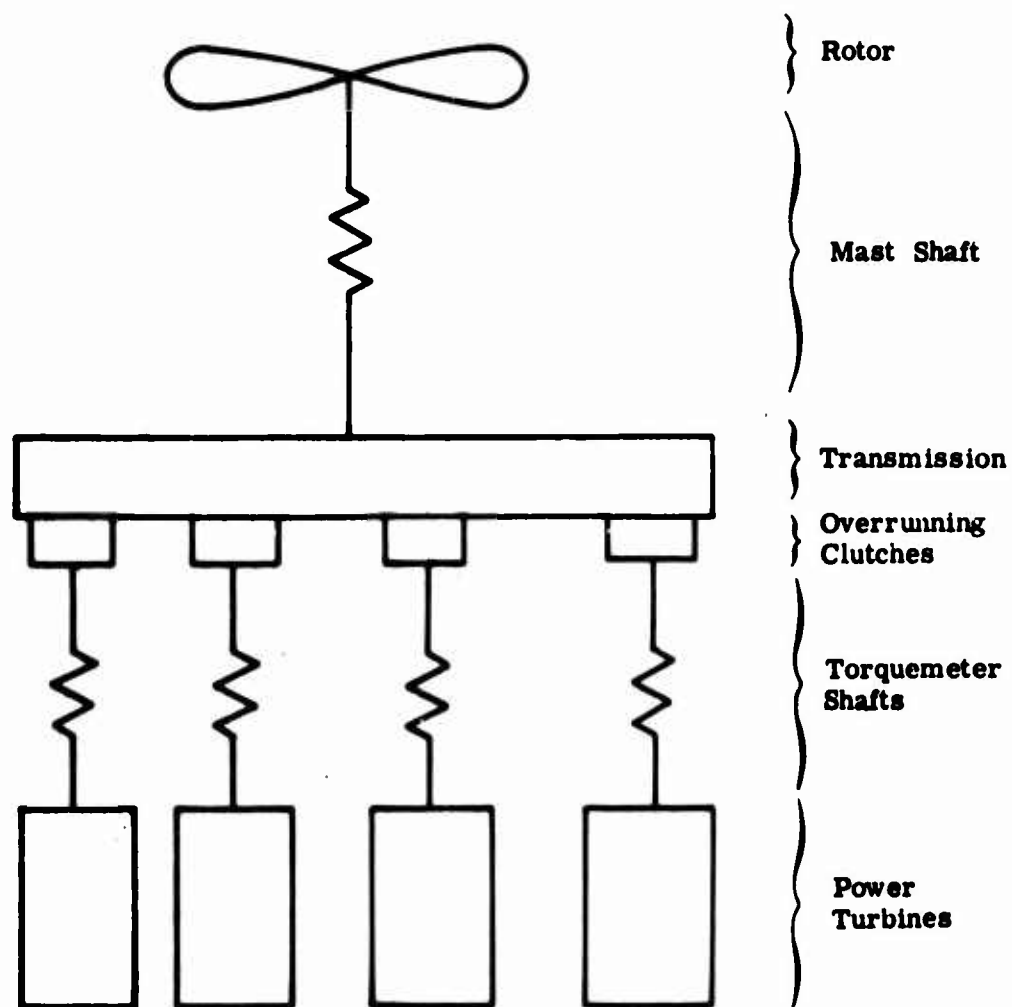


Figure 47. Rotor System Configuration.

Data defining the rotor system that was utilized are presented in the following paragraphs. The system torsional natural frequency is approximately 3 cycles per second. The rotor load was defined to be 5270 shaft horsepower at 45 degrees collective lever (CL) at 100-percent rotor speed. The rotor power varies in proportion to the rotor speed cubed. At zero collective lever, the rotor load is zero (an in-flight condition assumed). A linear load variation with collective between 0 and 45 degrees was provided.

Although the rotor system model was simplified over that of an actual helicopter rotor, it was adequate for the coordinated control system dynamic studies.

Helicopter Rotor

- $100\% N_r = 150 \text{ rpm}$
- Design SHP = $5270 \times \text{number of engines}$
- I_r (Reference 150 r. p. m.) = $33,000 \text{ slug-square feet} \times \text{number of engines}$

Helicopter Mast Shaft

- K_s (Reference 150 rpm) = $1,800,000 \text{ foot-pounds/radian} \times \text{number of engines}$

Helicopter Transmission

- I_{TRANS} (Reference 150 rpm) = $1650 \text{ slug-square feet} \times \text{number of engines}$

Engine Torquemeter Shafts

- K_{TM} (Reference 13,820 rpm) = $21,417 \text{ foot-pounds/radian (one per engine)}$

Engine Power Turbines

- $100\% N_{\text{PT}} = 13,820 \text{ rpm}$
- I_{PT} (Referenced 13,820 rpm) = $0.5 \text{ slug-square feet (one per engine)}$

CONTROL SYSTEM

A choice of several different control system combinations was provided in the simulation. The different options that could be simulated are as follows:

- Single power turbine governor with control differences
- Individual power turbine governors with control differences
- Individual governors, all identical
- Collective lever coordination
- Isochronous governing

- Proportional power turbine governor with lagged gain reset
- Proportional power turbine governor without lagged gain reset
- With load sharing control operating
- Without load sharing control operating
- Load sharing control design with highest torque as reference
- Malfunction detector on with power turbine governor reset capability
- Malfunction detector off without power turbine governor reset capability

The gas producer control is a functional design which is similar to Figure 17. This design provides an acceleration and deceleration fuel schedule and gas producer governor settings for ground idle, military, and emergency power operation. The acceleration and deceleration schedules are provided as tables in the simulation. The gas producer governor is defined as a speed set point and a gain. Dynamic first-order lags are employed on the gas producer speed sensor and the fuel metering valve, typical of a hydromechanical fuel control.

The power turbine governor is basically a proportional governor with a lagged gain reset (Figure 1). The governor is defined as a speed setting and a forward loop proportional gain, with a feedback gain and a feedback lag time constant. By specifying certain system design values, the forward loop and feedback loop gains are automatically computed within the simulation. The governor speed setting may be affected by the collective lever, load sharing control, reset feedback, isochronous function, or malfunction detector. The control difference characteristics illustrated in Figure 30 and Figure 40 are also included in the governor simulation, affecting the governor gain and speed setting.

Two load sharing controls are provided in the simulation, differing by the reference parameter that is employed. In one, the reference is the maximum engine torque, while the other is the average torque. The functional designs of both are similar to Figure 27. The control scheduling is represented as a gain, with limits on the governor speed trim authority allowed. A first-order lag function is provided in the load sharing control to represent its dynamic characteristic.

The malfunction detector is represented as a computation network based on sensing gas producer speeds and/or torques. Using previously determined settings ensures proper operation of this component and the detector.

POWER SYSTEM SIMULATION

The multiengine power simulation is a combination of the engine, rotor system, and control system models. This simulation has been set up to provide the following capabilities:

- Operate as a two-, three-, or four-engine system
- Conduct collective lever versus time transients
- Demonstrate an engine power failure transient
- Select idle operation of an engine
- Select emergency operation capability for engines
- Select OFF operation of an engine
- Operate with closed-loop load sharing control ON or OFF
- Operate with malfunction detector system ON or OFF
- Operate with engines of different steady state and/or dynamic performance characteristics
- Vary certain critical control system gains for evaluation
- Operate with single governor or individual governors

The simulation will also allow operation with any of the control system configurations previously described.

The power system has been programmed for the IBM 7094 digital computer. The Source Program Listing presented herein includes the computation and logic that make up the multiengine power system simulation.

The dynamic computation consists of a step calculation approach that requires no iteration loops. Instead, the dynamic computations assume that the value of the variable established in the previous calculation time period determines the dynamics over the next time increment, to arrive at a new value at the end of that time increment. This technique provides accurate results because the computer time increment is made small, making the difference between the previous value and the average value insignificant.

The input parameters to this program are presented and defined herein. The normal values are also listed which are input data values permanently stored in the program. The input data format is also presented, indicating that the normal (stored) values will be employed unless changed by inputting new values for any variable.

When the number of engines in the system (NENGOP) is less than four, zeros will be printed in the columns for engines not being employed. The theta printed out is the rotor mast shaft twist in radians.

PROGRAM INPUT PARAMETERS

CL vs TIME	Four-point input table with first-order interpolation. Minimum CL is 0.0. Maximum CL is 45.0. Time is in seconds.
NENGOP	Integer Number, number of engines in the system design. Normally 4.
SSDRP	Power turbine governor steady-state design droop from zero to max HP. Percent ΔN_2 . Normally 5 percent.
DYND RP	Power turbine governor design droop with no dynamic reset, from zero to max HP. Percent ΔN_2 . Normally 10 percent.
NCT	Integer Number, governor concept and control tolerance selection. Normally 1. 0 - Identical, individual governors 1 - Individual governors with tolerances 2 - Single governor with tolerances
CMPDT	Compute time increment, in seconds. Normally 0.02.
WRITDT	Print time increment, in seconds. Normally 0.1.
FNLTME	Final time for calculation, in seconds. Normally 15.0.
TMIDL	Time which, when exceeded, Number 1 engine selects ground idle, in seconds. Normally 100.0.
EMGTM	Time which, when exceeded, emergency power capability is selected on all engines, in seconds. Normally 100.0.
IEMD	Integer Number. Malfunction detector selector key. Normally 1. 0 - Detector is operative 1 - Detector is OFF
QE	Malfunction detector torque difference setting factor (pound-feet). Normally 4000.0.

RN2MD	Power turbine governor speed setting reset by malfunction detector to provide lead. (Percent N ₂). Normally 175.0.
DNE	Malfunction detector N ₁ difference setting factor (%). Normally 7.5.
IISC	Integer Number. Load sharing control selector key. Normally 0. 0 - Control is operative 1 - Control is OFF
GN2LS	Load sharing control gain (ΔN_2 Set/ ΔQ , rpm/pound-foot). Normally 7.0.
FMXDN2	Maximum power turbine governor speed reset of load sharing control (rpm). Normally 290.0.
TAUQ	Time constant of load sharing control, seconds. Normally 0.05.
TAUR	Power turbine governor reset lag, in seconds. Normally 0.2.
ERM	Transient response multiplier on engine Number 1, multiplier on N ₁ acceleration. Unitless. Normally 1.0.
EPD	SHP differential factor on engine Number 1, added to engine shaft horsepower. Normally 0.
FAIL	Time for failure of Number 1 engine, in seconds. Normally 100.0.
GINTEG	Isochronous governor integrator gain ($\frac{\Delta PTL/\Delta t}{\Delta N_2}$, degrees/second/r. p. m.). Normally 0.

MULTIENGINE HELICOPTER LOAD SHARING SIMULATION
INPUT DATA FORMAT

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
TITLE OR IDENTIFICATION (Columns 2 thru 72)																																																																															
1																																																																															
2																																																																															
3A																																																																															
3B																																																																															
PARAM CHAPT=.005,WRITOT=.005,FALTIME=.10,NCT=1,1DUMP=1,NENGOP=2,QE=350.,																																																																															
FAIL=50.,DYNORP=7.0SEND																																																																															
NOTE: Either line 3a or 3b above is required along with lines 1 and 2 to make up a complete set of data. Use 3a (exactly as shown) if there are no corrections to any of the normal values of the read-in parameters (except CL and time), which are defined on the input data sheets. To correct or override any or all of the normal values, a line or lines similar to 3b must be used (line 3b above is used for illustration). The read-in parameter symbols that must be used to override the normal values are defined on the input data sheets. The overrides need not be in any particular order. Symbols that start with the letters I, J, K, L, M or N require values with no decimal points. All other symbols must have values with decimal points.																																																																															
1 2 3 4 5 6 7 8 9																																																																															

OUTPUT PRINTOUT

INPUT DATA

CL TIME
13.30 0.00
45.30 1.00
45.00 5.00
45.30 15.00

NO. OF ENGINES = 4 GOVERNOR SELECTION = 1 MALFUNCTION DETECTOR SELECTION = 1 LOAD SHARING CONTROL SELECTION = 1
PCT. S.S. TEMP 5.000 PCT. DYN OPP 10.000 COMPUTE BY 0.020 WRITE BY 0.100 FINAL TIME 6.300 TMDL 100.000 ENGTH 100.000 RNDMD 175.000 OF 60.000
NE 5.000 GNZLS 17.000 MAX DM2 200.000 TAU0 0.350 TAU1 1.200 FPM 1.000 F00 0.000 FAIL 100.000 SINTER 0.000

OUTPUT RESULTS

TIME SECONDS	PERCENT NR	THETA RADIANS	PERCENT POWER	TURBINE SPEED	PERCENT GAS PRODUCTION	SPEED	PERCENT ENGINE	SHIFT TORQUE
0.00	107.00	0.023	100.00	100.00	100.00	100.00	100.00	100.00
0.10	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
0.20	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
0.30	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
0.40	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
0.50	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
0.60	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
0.70	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
0.80	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
0.90	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
1.00	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
1.10	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
1.20	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
1.30	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
1.40	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
1.50	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
1.60	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
1.70	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
1.80	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
1.90	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
2.00	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
2.10	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
2.20	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
2.30	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
2.40	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
2.50	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
2.60	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
2.70	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
2.80	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
2.90	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
3.00	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
3.10	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
3.20	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
3.30	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
3.40	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
3.50	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
3.60	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
3.70	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
3.80	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
3.90	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00
4.00	99.94	0.023	100.00	100.00	100.00	100.00	100.00	100.00

SOURCE PROGRAM PRINTOUT

```

DIMENSION TITLE(18),WFCDPX(15),HPY1(15),HPX1(9),WFMETY(9),HPX2(12)
1,SNY(12),HPX3(9),PCY(9),TN1SNS(13),WCPACY(13),WFMETX(42),SN1Z(7),
2TN1DOT(42),WFMETX(9),SHPY2(63),SHPY1(63),SHPY3(63),PCY2(63),CL(4),
3TIME(4),SN1(4),SN2(4),QQM(4),Y(4),Z(4),DN2ST(4),WFCDP(4),SHP(4),
4WFMET(4),PC(4),T1QM(4),DNREST(4),SN2GV(4),SN1SNS(4),SN1ST(4),HP(4),
5DNREQ(4),SN2ST(4),WCPN2(4),SNE1(4),WCPN1(4),WCPAC(4),WFREQ(4),
6SN1DOT(4),SHPA(3),SN2X(3),QENG(4),SN2P(4),QQMP(4)
NAMELIST/NAM/NENGOP,SSDRP,DYNDRP,NCT,CHPDT,WRITDT,FNLTIME,TMIDL,
1ENGTH,IEND,RN2MD,QE,DNE,ILSC,GNZLS,FMXDN2,TAUQ,TAUR,ERM,EPD,FAIL,
2IDUMP,GINTEG
NAMELIST/NAM1/PTL,GTN2G,G3N2G,RSTGN/NAM2/QMR,THMR/NAM3/SUMQ,WFCDP,
1SN2,HP,WFMET,SN1,PC,QQM,THQM,DNRST/NAM4/TIM,CLPOS,QMULT,L,REF,
2SMULT,REFQ,DN2S,DN2ST,SN2GV,DNREQ,WFREQ,SN2ST,WCPN2,SN1SN,SNE1,
3WCPN1,WCPAC,SN1DOT,SHPA,SHP,QENG,QTOT,QTRAN,SNTRN,QCL,SNMR,SNCNT
100 FORMAT(18A4)
101 FORMAT(8E9.2)
102 FORMAT( 65H0                                ***INP
1UT DATA***)
103 FORMAT( 63H0                                CL
1    TIME)
104 FORMAT(45X,2F9.2)
105 FORMAT(16H0 NO.OF ENGINES=12,22H    GOVERNOR SELECTION=12,33H    MAL
1FUNCTION DETECTOR SELECTOR=12,33H    LOAD SHARING CONTRL SELECTOR=
212)
106 FORMAT(115H)    PCT.S.S.DRP    PCT.DYN DRP    COMPUTE DT    WRITE DT
1    FINAL TIME    TMIDL    ENGTH    RN2MD    QE)
107 FORMAT(118H)    NE    GNZLS    MAX.DN2    TAUQ
1    TAUR    ERM    EPD    FAIL    GINTEG)
108 FORMAT(9F13.3)
109 FORMAT(118H)    TIME PERCENT THETA    PERCENT POWER TURBINE SPEED
1    PERCENT GAS PRODUCER SPEED    PERCENT ENGINE SHAFT TORQUE)
110 FORMAT(119H SECONDS    NR    RADIANS    NO.1    NO.2    NO.3    NO.4
1    NO.1    NO.2    NO.3    NO.4    NO.1    NO.2    NO.3    NO.4)
111 FORMAT(2F8.2,F8.3,12F8.2)
112 FORMAT( 67H0                                ***OUTPU
1T RESULTS***)
DATA WFCDPX/0.,2.,4.,4.364,4.78,5.125,5.5,5.85,6.4,7.0,7.575,8.33,
18.575,9.0,13./,HPY1/0.,0.,0.,0.,250.,500.,870.,1100.,1640.,2300.0,
23050.,4150.,4575.,5270.,5270./,HPX1/-500.,0.,75.,1950.,2850.,
33825.,4650.,5275.,6000./,WFMETY/485.,485.,775.,1250.,1500.,2000.,
42350.,2610.,2610./,HPX2/-500.,0.,500.,900.,1550.,2050.,2650.,3450.
5,4100.,4600.,5275.,6000./,SNY/81.75,81.75,84.,85.6,88.,89.8,91.8,
694.4,96.4,98.,100.,100./,HPX3/-500.,0.,1000.,1900.,2600.,3550.,
74200.,5275.,6000./,PCY/110.,110.,150.,185.,210.,240.,260.,290.,
8290./
DATA TN1SNS/78.7,80.,81.3,83.3,85.4,86.8,93.,96.,98.,100.,102.1,
1104.,106./,WCPACY/6.65,6.775,6.9,7.15,7.45,7.7,8.85,9.375,9.7,10.,
210.25,10.425,10.575/,WFMETX/40.,360.,800.,1000.,1200.,1540.,20.,
3490.,720.,940.,1340.,1700.,100.,380.,770.,1180.,1500.,1800.,200.,
4670.,1320.,1740.,2180.,2560.,900.,1180.,1500.,1940.,2400.,3060.,
51200.,1700.,2175.,2600.,3200.,3800.,1800.,2240.,2600.,3200.,3730.,
64400./,TN1DOT/-1450.,0.,1900.,2700.,3500.,4800.,-2100.,0.,1000.,
71950.,3550.,4900.,-3000.,-1750.,0.,1800.,3100.,4250.,-5250.,-3000.
8,0.,1800.,3500.,4900.,-4250.,-3025.,-1700.,0.,1750.,4125.,-5000.,

```

9-3150.,-1500.,0.,2000.,3875.,-4450.,-2950.,-1800.,0.,1500.,3425./,
 ASN12/80.,81.75,85.,90.,95.,100.,105./
 DATA WFMTX/3.,360.,480.,770.,1320.,1940.,2610.,3200.,4200./,
 1SHPY2/-830.,-350.,-210.,130.,720.,1250.,1600.,1750.,1940.,-650.,
 2-170.,0.,350.,990.,1560.,2000.,2220.,2400.,-410.,130.,300.,720.,
 31430.,2090.,2660.,3000.,3380.,0.,600.,800.,1270.,2110.,2920.,3640.

4,4110.,4540.,370.,1025.,1230.,1750.,2670.,3630.,4570.,5200.,5840.,
 5750.,1420.,1640.,2180.,3170.,4220.,5270.,6050.,7060.,1110.,1840.,
 62070.,2600.,3550.,4610.,5650.,6550.,7950./,SHPY1/-450.,-100.,10.,
 7300.,800.,1260.,1530.,1640.,1650.,-300.,75.,210.,510.,1050.,1520.,
 81880.,2050.,2250.,20.,440.,575.,900.,1490.,2050.,2540.,2890.,3350.,
 9,450.,950.,1100.,1500.,2200.,2910.,3560.,4040.,4650.,900.,1430.,
 A1600.,2020.,2770.,3550.,4310.,4900.,5760.,1410.,1930.,2100.,2900.,
 83260.,4100.,4990.,5700.,6740.,1830.,2350.,2530.,2950.,3730.,4580.,
 C5470.,6200.,7220./,SN2X/11056.,13820.,15202./
 DATA SHPY3/-1300.,-710.,-530.,-100.,580.,1140.,1500.,1630.,1640.,
 1-1150.,-550.,-340.,110.,840.,1450.,1860.,2030.,2040.,-850.,-230.,
 2-20.,480.,1340.,2060.,2580.,2800.,2920.,-290.,350.,580.,1100.,
 32000.,2840.,3620.,4130.,4580.,220.,840.,1060.,1600.,2590.,3590.,
 44550.,5310.,5410.,600.,1270.,1500.,2050.,3070.,4220.,5350.,6270.,
 57570.,1000.,1680.,1910.,2450.,3450.,4550.,5730.,6650.,8110./,
 6PCY2/84.,94.,98.,106.,119.,132.,137.,138.,139.,95.,106.,110.,118.,
 7132.,144.,152.,154.,155.,115.,128.,132.,141.,157.,170.,179.,184.,
 8188.,142.,157.5,162.,174.,192.5,208.,220.,227.5,235.,167.,183.,
 9188.5,201.,222.,243.,259.,269.,282.,183.,201.,207.,221.,245.,269.,
 A290.,305.,328.,192.,211.5,218.,232.,258.,284.,306.,323.,347./

1 NENGOP=4
 SSORP=5.
 DYNDRP=10.
 NCT=1
 CMPDT=.02
 WRITDT=.10
 FNLTME=15.
 TMIDL=100.
 EMGTM=100.
 IEMD=1
 RN2MD = 175.
 QE=400.
 ONE=5.
 ILSC=0
 GN2LS=17.
 FMXDN2=400.
 TAUQ=.05
 TAUR=.5
 ERM=1.
 EPD=0.
 FAIL=100.
 IDUMP = 0
 GINTEG = 0.
 READ (5,100)(TITLE(I),I=1,18)
 WRITE(6,100)(TITLE(I),I=1,18)
 WRITE(6,102)
 READ (5,101)(CL(I),TIME(I),I=1,4)
 WRITE(6,103)
 DO 2 I=1,4
 2 WRITE(6,104)CL(I),TIME(I)

```

READ (5,NAM)
DTRAT = WRITDT/CHPDT
WRITE(6,105)NENGOP,NCT,IEMD,ILSC
WRITE(6,106)
WRITE(6,108)SSDRP,DYNDRP,CHPDT,WRITDT,FNLTHE,TMIDL,ENGTM,RN2MD,QE
WRITE(6,107)
WRITE(6,108)ONE,GN2LS,FMXDN2,TAUQ,TAUR,ERM,EPD,FAIL,GINTEG
ENGOP = NENGOP
C INITIAL CALC. VALUES
DO 53 I=1,4
  SN1(I)=0.
  SN2P(I)=0.
53 QOMP(I)=0.

GTN2G = .03354821 /SSDRP
G3N2G = .03354821 /DYNDRP
RSTGN = (DYNDRP -SSDRP) /.03354821
IF (NCT.EQ.1)GO TO 52
DO63 K=1,4
63 Y(K) = 0.
  IF (NCT.EQ.2)GO TO 54
  DO55 K=1,4
55 Z(K)=1.
  GO TO 56
54 Z(1)= .94
  Z(2)= 1.06
  Z(3)= 1.0
  Z(4)= 1.04
  GO TO 56
52 Y(1) = 34.55
  Y(2) = 0.
  Y(3) = -34.55
  Y(4) = -34.55
  Z(1) = .85
  Z(2) = 1.15
  Z(3) = .85
  Z(4) = 1.0
56 SUMQ=0.
  TIM =0.
  SNMR= 150.
  SNTRN=150.
  SNCNT = 0.
  IF (IDUMP.NE.0)WRITE(6,NAM1)
  K =0
  L =0
62 K= K+1
  IF (K.LE.NENGOP)GO TO 57
  IF (GINTEG.NE.0.)GO TO 72
  DPTL =0.
  GO TO 73
72 DPTLM = 1.5*(SSDRP+6.)
  DPTL = .02170767/GTN2G*(WFCOP(1)-6.6818)
  PTL = 75.-1.5*SSDRP

```

```

73 QMR = SUMQ / .01085383
   QTOT = SUMQ
   THMR = QMR / 1800000. / ENGOP
   IF (IDUMP.NE.0) WRITE(6,NAM2)
   GO TO 65
57 SN2(K)=13820.
   SN2GV(K)=13820.
   HP(K)=CL(1)*117.1111
   CALL DISCOT(HP(K),0,HPX1,WFMETV,0,-010,9,0,WFMET(K))
   CALL DISCOT(HP(K),0,HPX2,SNV,0,-010,12,0,SN1(K))
   CALL DISCOT(HP(K),0,HPX3,PCV,0,-010,9,0,PC(K))
   WFCDP(K)=WFMET(K)/PC(K)
   IF (ILSC.LE.0) GO TO 58
   DN2ST(K)=0.
   GO TO 59
58 DN2ST(K)=(1.-CL(1)/45.)*138.2*SSDRP-V(K)-(9.-WFCDP(K))/GTN2G/Z(K)
59 QQM(K)= HP(K) *5252. /SN2(K)
   SUMQ = SUMQ + QQM(K)
   DNRST(K) =(WFCDP(K) -9.)*RSTGN
   SN1SNS(K)= SN1(K)
   GO TO 62
C   WRITE OUTPUT VALUES
65 WRITE (6,112)
   IF (IDUMP.NE.0) WRITE(6,NAM3)

   WRITE (6,109)
   WRITE(6,110)
3  SNMRP = SNMR / 1.5
   DO 4 K=1,NEVGOP
   SN2P(K)= SN2(K) / 138.2
4  QQMP(K)= QQM(K) *.04993128
   WRITE (6,111) TIM,SNMRP,THMR,(SN2P(I),I=1,4),(SN1(I),I=1,4),(QQMP(I),I=1,4)
50 TIM= TIM + CMPDT
   IF (TIM.GT.FNLTIME) GO TO 1
   CALL DISCOT(TIM,0,TIME,CL,0,-010,4,0,CLPOS)
   IF (GINTEG.LE.0) GO TO 70
   DPTL = DPTL+GINTEG*(150.-SNTRN)*CMPDT
   DPTL=AMIN1(DPTL,DPTLM)
   DMPTLM=-DPTLM
   DPTL=AMAX1(DPTL,DMPTLM)
   GO TO 71
70 P1L = 75.-(45.-CLPOS) *.06666666 * SSDRP
71 IF (TIM.LT.TMIDL) GO TO 5
   NECL=1
   GO TO 6
5  NECL=2
6  IF (TIM.LT.EMGTM) GO TO 7
   NECL=3
   DO 11 I=1,NEVGOP
11 SN1ST(I) = 104.5
   GO TO 10
7  DO 9 I=1,NEVGOP
9  SN1ST(I) = 101.0

```

```

      IF (NECL.EQ.1)SN1ST(1)=80.3
10  IF (IEND.LE.0)GO TO 12
      DN2MD = 0.
      GO TO 16
C  MALFUNCTION DETECTOR
12  IF (L.GT.0)GO TO 15
      IF (NENGOP.LE.1)GO TO 13
      IF (TIM.GE.TMIDL)GO TO 14
      IF (ABS(QQM(1)-QQM(2)).GE.QE)GO TO 15
      IF (ABS(SN1(1)-SN1(2)).GE.ONE)GO TO 15
14  IF (NENGOP.LE.2)GO TO 13
      IF (ABS(QQM(2)-QQM(3)).GE.QE)GO TO 15
      IF (ABS(SN1(2)-SN1(3)).GE.ONE)GO TO 15
      IF (NENGOP.LE.3)GO TO 13
      IF (ABS(QQM(3)-QQM(4)).GE.QE)GO TO 15
      IF (ABS(SN1(3)-SN1(4)).GE.ONE)GO TO 15
13  DN2MD = 0.
      L=0
      GO TO 16
15  IF (NECL.EQ.3)GO TO 18
      DO 17 I=1,NENGOP
17  SN1ST(I) = 124.5
18  DN2MD = RN2MD
      L=1
16  IF ((ILSC.GT.0).OR.(NENGOP.EQ.1))GO TO 19
      IF (ILSC.EQ.0)GO TO 80
C  ALTERNATE LOADSHARING CONTROL
      K=0
      IF (TIM.GE.TMIDL)GO TO 81
      QREF = QTOT/ENGOP
      GO TO 82
81  QREF = QTOT/(ENGOP-1.)
      DN2ST(1) = 0.
82  K=K+1
      IF (K.GT.NENGOP)GO TO 19
      DN2S = GN2LS*(QREF-QQM(K))
      TMXDN2 = -FMXDN2
      DN2S = AMAX1(DN2S,TMXDN2)
      DN2S = AMIN1(DN2S,FMXDN2)
      DN2ST(K) = DN2ST(K)+(DN2S-DN2ST(K))* (1.-1./EXP(CMPDT/TAUQ))
      GO TO 82
C  LOAD SHARING CONTROL
80  IF (NENGOP.EQ.2)GO TO 20
      IF (NENGOP.EQ.3)GO TO 21
      QREF =AMAX1(QQM(1),QQM(2),QQM(3),QQM(4))
      GO TO 22
21  QREF =AMAX1(QQM(1),QQM(2),QQM(3))
      GO TO 22
20  QREF =AMAX1(QQM(1),QQM(2))
22  K=0
      IF (TIM.LT.TMIDL)GO TO 24
      DN2ST(1) = 0.
24  K=K+1
      IF (K.GT.NENGOP)GO TO 19

```

```

23 DN2S = GN2LS *(QREF - QQM(K))
   IF (DN2S.GE.0.)GO TO 25
   DN2S = 0.
25 IF (DN2S.LE.FMXDN2)GO TO 26
   DN2S = FMXDN2
26 DN2ST(K) = DN2ST(K) + (DN2S - DN2ST(K)) * (1. - 1./EXP(CMPDT/TAUQ))
   GO TO 24
C  ENGINE CONTROL CALC.
19 K=0
33 K=K+1
   IF (K.GT.NENGOP)GO TO 27
   IF (TIM.LT.FAIL)GO TO 32
   IF (K.GT.1)GO TO 32
   WFMET(K) = 0.
   GO TO 33
32 IF (NCT.EQ.2)GO TO 34
   SN2GV(K) = SN2(K)
   GO TO 35
34 SN2GV(K) = SN2(1)
   WFCOP(K) = WFCOP(1)
35 DNREQ(K) = RSTGN *(WFCOP(K) - 9.)
   DNRST(K) = DNRST(K) + (DNREQ(K) - DNRST(K)) * (1. - 1./EXP(CMPDT/TAUR))
   PTLPD = PTL + DPTL
   SN2ST(K) = 10365. + PTLPD /.02170767 + V(K) + DN2ST(K) + DNRST(K)
1  +DN2MD
   WCPN2(K) = 9. - (SN2GV(K) - SN2ST(K)) * G3N2G * Z(K)
   SN1SNS(K) = SN1SNS(K) + (SN1(K) - SN1SNS(K)) * (1. - 1./EXP(20.*CMPDT))
   SNE1(K) = SN1SNS(K) - SN1ST(K)
   IF (SNE1(K).GE.(-20.))GO TO 36
   SNE1(K) = -20.
36 WCPN1(K) = 9. - SNE1(K) * 1.C4
   CALL DISCOT(SN1SNS(K), 0, TN1SNS, WCPACY, 0, -010, 13, 0, WCPAC(K))
   IF (WCPAC(K).LT.WCPN2(K))GO TO 37
   IF (WCPN2(K).LT.WCPN1(K))GO TO 39
37 IF (WCPAC(K).LT.WCPN1(K))GO TO 38
   WFCOP(K) = WCPN1(K)
   GO TO 40
38 WFCOP(K) = WCPAC(K)
   GO TO 40
39 WFCOP(K) = WCPN2(K)
40 SAV1 = .4 * WCPAC(K)
   IF (WFCOP(K).GE.SAV1)GO TO 41
   WFCOP(K) = SAV1

41 WFREQ(K) = WFCOP(K) * PC(K)
   WFMET(K) = WFMET(K) + (WFREQ(K) - WFMET(K)) * (1. - 1./EXP(50.*CMPDT))
   GO TO 33
C  ENGINE CALC.-GAS PRODUCER ROTOR
27 K=0
   AJ=0.
   QTOT=0.
43 K=K+1

```

```

IF (K.GT.NENGOP)GO TO 45
IF (TIM.LT.FAIL)GO TO 42
IF (K.GT.1)GO TO 42
SN1(K) =0.
SN2(K) =0.
QQM(K) =0.
GO TO 43
42 CALL DISCOT(WFMET(K),SN1(K),WFMETX,TN1DOT,SN1Z,-11,42,7,SN1DOT(K))
IF (K.LE.1)SN1DOT(K)= SN1DOT(K)* ERM
SN1(K) = SN1(K) + SN1DOT(K) *CMPDT *.004826338
CALL DISCOT(WFMET(K),SN1(K),WFMTX,SHPY1,SN1Z,11,63,7,S4PA(1))
CALL DISCOT(WFMET(K),SN1(K),WFMTX,SHPY2,SN1Z,11,63,7,S4PA(2))
CALL DISCOT(WFMET(K),SN1(K),WFMTX,SHPY3,SN1Z,11,63,7,S4PA(3))
CALL DISCOT(SN2(K),0,SN2X,SHPA,0,-20,3,0,SHP(K))
IF (K.LE.1)SHP(K)=EPD + SHP(K)
QENG(K) = SHP(K) * 5252. /SN2(K)
QQM(K) = QENG(K)
IF ((SN2(K).LT.(SNTRN/.01085390)).OR.(QENG(K).LT.0.))GO TO 67
QTOT = QTOT + QQM(K)
AJ=AJ+1.
67 SN2(K) =SN2(K) +CMPDT*19.1 *QENG(K)
CALL DISCOT(WFMET(K),SN1(K),WFMTX,PCY2,SN1Z,11,63,7,PC(K))
GO TO 43
C HELICOPTER TRANSMISSION AND ROTOR SYSTEM
45 QTRAN = QTOT /.01085383
DENM = ENGOP*1650. +AJ*4244.275
SNTRN = (QTRAN -QMR) /.1047198 *CMPDT /DENM +SNTRN
QCL = CLPOS *ENGOP* SNMR**2 *.1822423
THMR = THMR +(SNTRN -SNMR) *.1047198 *CMPDT
QMR = THMR * ENGOP * 180000.
SNMR = SNMR + (QMR-QCL) /.1047198 *CMPDT /ENGOP /33000.
ARG2 =SNTRN*92.13333
K=0
69 K=K+1
IF (K.GT.NENGOP)GO TO 68
SN2(K) = AMIN1(SN2(K),ARG2)
GO TO 69
C WRITE BYPASS CALC.
68 SNCNT = SNCNT +1.
IF (IDUMP.EQ.0)GO TO 66
WRITE (6,NAM2)
WRITE (6,NAM3)
WRITE (6,NAM4)
66 IF (SNCNT.LT.DTRAT)GO TO 50
SNCNT = 0.
GO TO 3
END

```

DEFINITION OF AN OPTIMUM SYSTEM DESIGN AND REQUIRED SCHEDULING

The control system evaluations provide for the definition of an optimum engine control system for the multiengine helicopter. The major features of this system are as follows:

- Rotor speed governing by engine power modulation between zero and maximum power
- Individual power turbine governors with closed-loop load sharing on torque
- Emergency power operation capability, selected automatically by a malfunction detector or manually
- Automatic turbine temperature limiting during steady-state operation
- Governing mode that provides stability in normal governing, in de-coupled operation, and with extraneous torsional excitations
- Rapid engine power response to load changes, utilizing collective lever coordination to provide anticipation of large load changes
- Automatic sequencing and metering of fuel flow during engine starting
- Engine control by gas producer governing during ground idle or locked rotor operation
- Capability of operating with any engine at ground idle or shutdown, retaining rotor speed governing and load sharing on the other engines

Figure 48 is a block diagram of a coordinated control system for a two-engine helicopter. Each engine will employ a gas producer fuel control, a turbine temperature limiter, a power turbine governor-load sharing control, and a malfunction detector.

In this diagram, the power turbine governor-load sharing control, the turbine temperature limiter, and the malfunction detector are represented as electrical-electronic designs. This design selection is not meant to indicate that this is the optimum method of implementation. This diagram is meant to indicate the components required in the system and their interrelationship. The actual selection of the type of design (i. e., electronic, pneumatic, hydromechanical, etc.) would be dependent on the type of engine parameter sensors that may be employed and the design mechanization study results.

The following paragraphs summarize the functional design and scheduling required of the different system components.

GAS PRODUCER CONTROL AND TURBINE TEMPERATURE LIMITER

Design

The functional requirements of these two components are defined in Figure 17. The gas producer control would be a hydromechanical design. As previously indicated, the turbine temperature limiter would be an electronic component.

The input signals or parameters to the gas producer control are as follows:

- Gas producer lever position
- Gas producer speed
- Compressor inlet air temperature
- Compressor air pressure, inlet or discharge
- Trim signal from turbine temperature limiter control
- Emergency selection signal from malfunction detector
- Power turbine governor signal

These signals are utilized to accomplish the computation and logic functions required to position the fuel metering valve correctly and to sequence the fuel cutoff valve. The final output of the control is metered fuel flow.

Scheduling

The turbine temperature control scheduling characteristics were defined as follows:

- Proportional gain:
 - $\Delta N_1 \text{ request} / \Delta \text{temperature error} = 0.015 \text{ percent}/^\circ\text{F}$
- Integrator gain:
 - $\Delta N_1 \text{ request} / \Delta \text{time} / \Delta \text{temperature error} = 0.009 \text{ percent} / \text{second}/^\circ\text{F}$
- Limiter authority:
 - Maximum $\Delta N_1 \text{ request} = 4 \text{ percent}$

The gas producer control scheduling employed is defined as follows:

- Governor gain:
 - $\Delta W_f / \text{CDP} / \Delta N_1 \text{ error} = 20 \text{ percent} / \text{percent}$
- Governor speed setting:
 - Ground idle (30 degrees GPL) = 80 percent
 - Military (90 degrees GPL) = 100 percent
 - Emergency = 104.5 percent

- Temperature compensation:
 - See Figure 49
- Start acceleration and deceleration schedules:
 - See Figure 50
- Mechanical fuel cutoff
 - Closed at GPI, less than 3 degrees
 - Open at GPI, greater than 15 degrees
- Start sequencing of fuel cutoff:
 - Closed at N_1 less than 15 percent
 - Open at N_1 greater than 15 percent

POWER TURBINE GOVERNOR-LOAD SHARING CONTROL

Design

The basic functional requirements of the power turbine governor are defined in Figure 1. The functional design of the load sharing control is defined in Figure 27. The two designs are combined to form a single electronic component, with each engine requiring a separate unit.

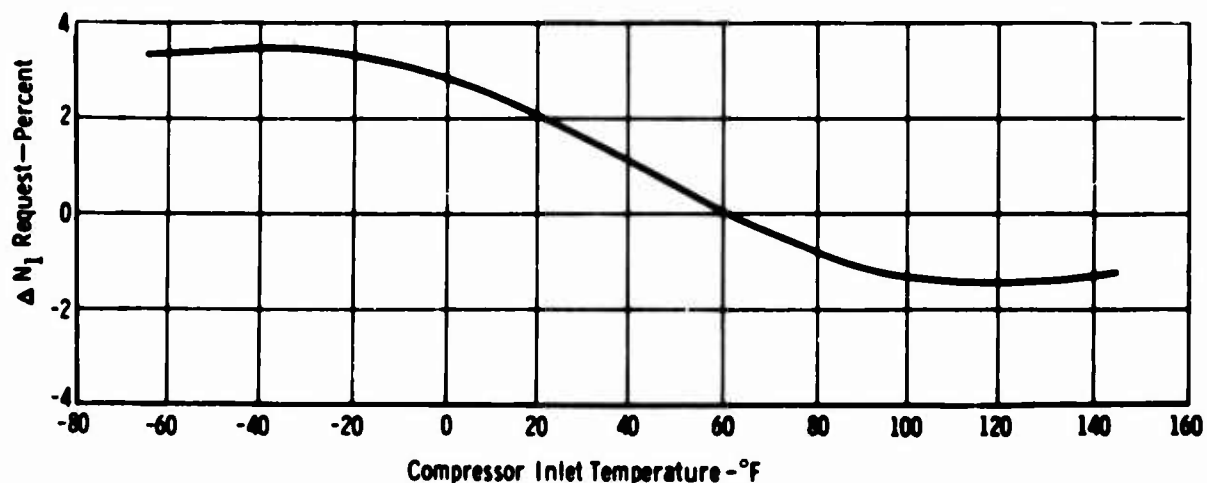


Figure 49. Temperature Compensation Schedule.

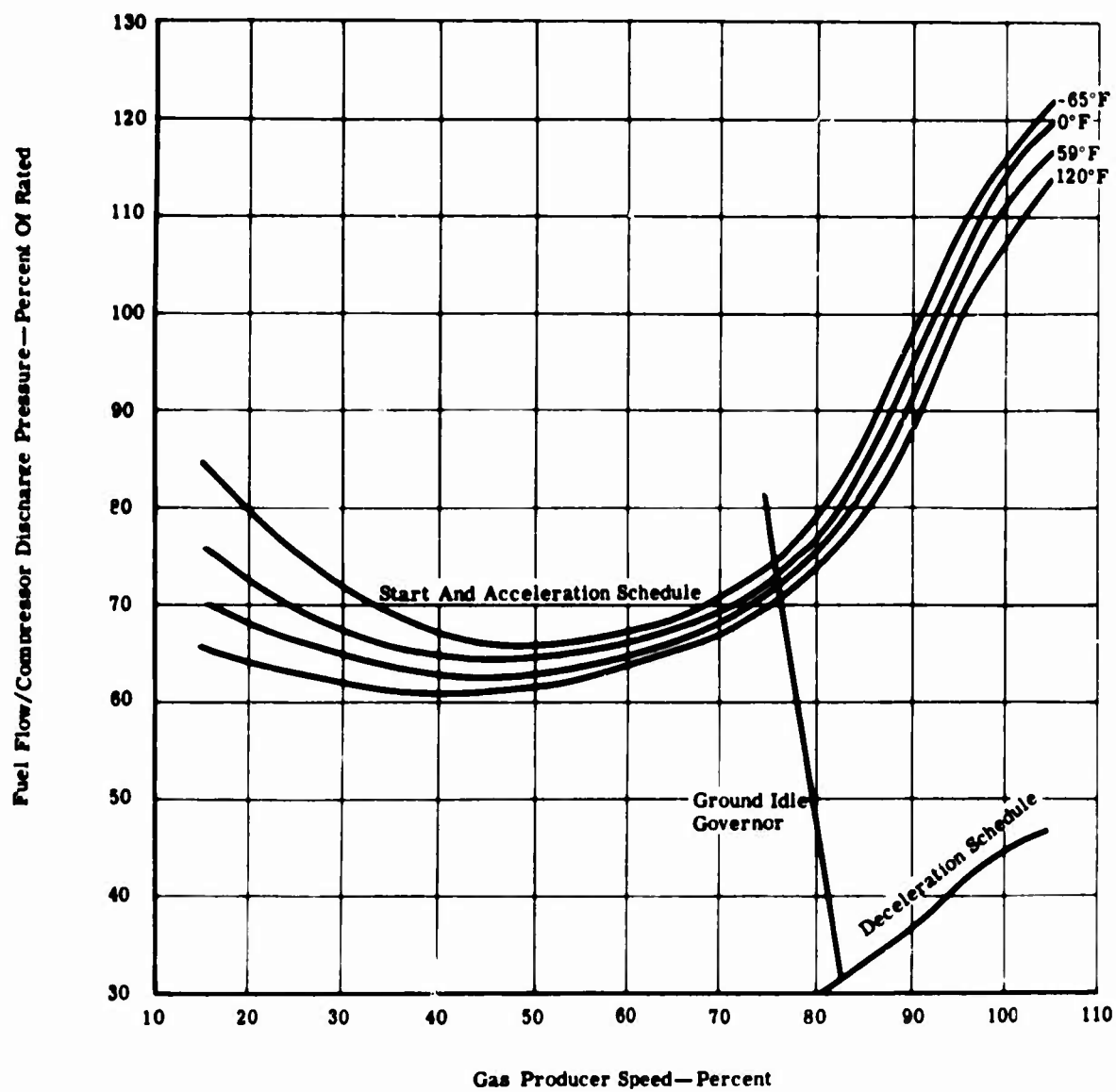


Figure 50. Gas Producer Control Fuel Schedules.

The input signals are as follows:

- Power turbine lever position
- Power turbine speed
- Torquemeter sense
- Amplified torque signals of the other engines (from their power turbine governor-load sharing controls)

The outputs of the control component(s) are an electrical signal to be utilized by the gas producer for fuel scheduling and an amplified torque signal to be used in the load sharing controls of the other engines.

Scheduling

The power turbine governor scheduling requirements were defined as follows:

- Proportional gain:
 - $\Delta W_f / \text{CDP request} / \Delta N_2 \text{ error} = 5.15 \text{ percent/percent}$
- Reset gain:
 - $\Delta N_2 \text{ set} / \Delta W_f / \text{CDP} = 0.097 \text{ percent/percent}$
- Reset lag Time Constant:
 - $\text{TAUR} (\tau_r) = 0.2 \text{ second}$
- Governor speed setting range:
 - Maximum $N_2 \text{ set} = 105 \text{ percent}$
 - Minimum $N_2 \text{ set} = 75 \text{ percent}$

The load sharing control scheduling requirements were defined as follows:

- Proportional gain:
 - $\Delta N_2 \text{ trim} / \Delta Q_{\text{error}} = 1.0 \text{ to } 2.5 \text{ percent/percent}$
- Trim authority limit:
 - Maximum $\Delta N_2 \text{ trim} = 2.1 \text{ percent}$
- Load sharing control dynamics (lag time constant):
 - $\text{TAUQ} = 0.05 \text{ to } 0.2 \text{ second}$

MALFUNCTION DETECTOR

Design

The malfunction detector is to be an electronic component. This component receives as input signals a gas producer speed signal from each engine, discriminates to select the highest as a reference, and then compares each individual speed signal to the reference. If any differential is greater than the predetermined safe value, the detector generates an output signal indicating a malfunction.

A separate circuit is required for each engine of the multiengine system but is combined in a single detector component. Deactivation switches operated by the engine condition control levers in the cockpit are employed to disarm the appropriate circuits when an engine is shut down or reduced to ground idle.

Input signals to this device are also employed to allow arming-disarming of the malfunction detector or to manually override the detector logic and artifically signal a malfunction, causing selection of emergency.

Scheduling

The scheduling requirements of this component are as follows:

- Differential speed setting:
 - ΔN_1 limit = 5 percent
- Output signal level:
 - Cockpit selection switch at automatic—normal = 0 volts and with malfunction = 24 volts
 - Cockpit selection switch at emergency—24 volts
 - Cockpit selection switch at off—0 volts
- Condition lever switch setting (one for each engine control lever):
 - Circuit armed at fly
 - Circuit disarmed at less than fly

CONCLUSIONS

POWER TURBINE GOVERNING MODE

The power turbine governing mode for any helicopter gas turbine engine should be a proportional fuel governor with a gain reset function operating through a time lag. The principal reason for preferring this mode is that it provides excellent torsional stability.

The lagged gain reset action provides a low gain at the high input frequencies, while maintaining a steady-state gain that is suitably high for accurate speed control (5-percent droop). This design provides flexibility. By proper selection of the reset gain and lag time constant, the fuel control system can be made compatible with engine-rotor systems of widely differing dynamic characteristics.

The power turbine governor action should be integrated into the gas producer control computer section to effectively utilize the fuel limit schedules and pressure compensation established therein.

SINGLE VERSUS INDIVIDUAL POWER TURBINE GOVERNOR

The use of separate (individual) power turbine governors on each engine in the system, rather than a single governor to control all engines, is desirable for best system operation with engine or control malfunctions and autorotation. The separate governor approach provides maximum system reliability in that the failure of any engine or control will not prevent the normal operation of the other engine systems. This would not be true with a single governor. The separate governors also provide direct control and maintain proper engine performance during autorotation because they directly sense the speed of the decoupled turbine. The single governor approach would not provide proper control of all engines in the event that one or more engines become decoupled from the rotor.

LOAD SHARING

A closed-loop load sharing control is required to trim to zero the power unbalance that would otherwise occur due to control and engine variations in production and service. The steady-state power differences between engines in a system may be as high as 38 percent without the load sharing control. This is unacceptable for normal operation because it can reduce the service life of the transmission system parts and lengthen the power recovery time in the event of an engine malfunction. The unbalanced power condition would also complicate the pilot's job.

The closed-loop load sharing control parameter should be engine torque. Matching of torque or gas producer speed would be satisfactory with regard to eliminating the major differences caused by control variations, but gas producer speed would not account for engine variations. The helicopter requirements are most completely met by matching the engine torques.

The load sharing control should be based on a floating master concept, with the reference torque being that of the highest torque engine. With this mode, the power levels of the low power engines would be increased to match that of the highest engine. Utilizing the highest torque engine as the reference is desirable because it prevents the low power engine from affecting the operation of the other engines. This is desirable when considering engine power failures, power depreciation, or engine operation while turbine temperature or gas producer speed is automatically limited. The result is that the maximum available power will be provided at all times.

COLLECTIVE LEVER COORDINATOR (ANTICIPATOR)

Coordination of the helicopter collective lever and power turbine governor levers is required to trim out the small steady-state speed variation with a load typical of a proportional (droop) governor design. The result is an acceptable steady state-rotor speed variation of less than 2 percent. This lever coordination also provides an anticipation signal to the engine controls on collective lever load transients, thereby minimizing the transient rotor speed variations.

ISOCRONOUS GOVERNING

Closed-loop isochronous governing is not desirable. Trim of the proportional governor by an isochronous governor (integrating component which senses speed error), rather than the collective lever, would result in zero rotor speed variation at steady state. However, the large transient rotor speed variations that would result due to large and rapid load changes would not be acceptable. These are due to the low integrator rate required for stability and the lack of a load change anticipation signal.

MALFUNCTION DETECTOR

An emergency power rating on the engines is required. Both manual and automatic selection capabilities must be provided. An automatic selection would be made by a signal generated within an engine-control malfunction detector. The malfunction detector is required to eliminate the delay associated with the pilot's detection and reaction time, and to enable safe continuation of aircraft operation when in a critical flight maneuver. Manual selection is required for a condition where an engine malfunction has not occurred but the situation warrants emergency power operation.

The detector must utilize gas producer speed, analyzing the speed differential between engines to determine the occurrence of a malfunction. When the differential between the highest and lowest engine exceeds a predetermined setting (5 percent), a malfunction would be signaled. Engine condition control lever (power lever) switches must be employed to deactivate portions of the detector in the event that an engine is shut down by the pilot.

TURBINE TEMPERATURE LIMITING

Closed-loop steady-state turbine temperature limiting is required to allow the utilization of the maximum power available from the multiengine system without exceeding the limit on any engine. Open-loop limiting is not satisfactory because of the extreme effect that exceeding this limit has on the engine's structural integrity, and the performance loss that would result with limiting to a low temperature level.

Open-loop limiting during starting and transients can be employed because the fuel scheduling margins between maximum temperature operation and minimum acceptable transient performance are normally sufficient to enable satisfactory scheduling. The currently available temperature sensing mechanisms are also too slow for transient limiting.

TORQUE LIMITING

The significant torque limits will be those of the helicopter transmission rather than those of the engine. Limiting engine power (fuel flow) by the engine control system is not desirable because there are certain conditions where the pilot may elect to exceed the helicopter red-line limit. Torque limiting must be accomplished by the pilot's manually limiting the loading with collective and/or cyclic pitch.

TWO-, THREE-, OR FOUR-ENGINE SYSTEMS

There are no significant differences in the control requirements for systems with different numbers of engines. The only difference is associated with the number of engine signal inputs and computation circuits that are required in the load-sharing controls and malfunction detector.

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Engine Helicopter Load Sharing						
Engine Helicopter Automatic Load Sharing						
Turbine Governing						
Propeller Control						
Engine Governing-Load Sharing						
Turbine Engine Simulation						
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